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ARS-33

May 1986

A Modular Energy Balance Program Including Subroutines for Greenhouses and Other Latent Heat Devices

Abstract

Kimball, Bruce A. 1986. A Modular Energy Balance Program Including Subroutines for Greenhouses and Other Latent Heat Devices. U.S. Department of Agriculture, Agricultural Research Service, ARS–33, illus. 360 p.

A computer program is presented for simulating the thermal performance and the energy and water uses of greenhouses. The program is modular and has many subroutines, each of which simulates some energy-related device using energy balance techniques. Latent heat exchange is also included so that evaporation from plants, soil, cooling towers, and other objects can be accounted for. The list of devices includes greenhouses, thermostats, pumps, fans, flow tees, sensible heat exchangers, latent plus sensible heat exchangers, solar collectors, tanks, heaters, night sky radiators, evaporative air coolers, rock beds, curtain heat exchangers, and passive storages. A mathematical model is presented for each device.

The program is highly versatile because the user can specify at run time those devices he or she wishes to include in a particular run and how they are connected (wires, pipes, ducts). The program has virtually no size limit on most computer systems because the individual subroutines can be stored on disk as overlay modules. Detailed instructions for using the program are included, along with examples of a simple greenhouse system and of a solar greenhouse system.

Keywords: energy balance, energy storage, energy use, computer program, cooling, greenhouse, heat exchanger, heating, modeling, modular program, night sky radiator, radiator, rock bed, simulation, solar collector, solar greenhouse, submodels, subroutines, thermal performance, thermostat

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A Modular Energy Balance Program Including Subroutines for Greenhouses and Other Latent Heat Devices

By B. A. Kimball

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By Bruce A. Kimball[1]

Introduction

To conserve energy and water, new greenhouse designs and methods for heating and cooling greenhouses are needed. Computer models of greenhouses and of heating and cooling devices can be used to help assess the feasibility of the new designs. This manual presents a modular energy balance model (MEB) which combines submodels of greenhouses with submodels of many other energy-related devices. The MEB model is versatile because the user can connect the submodels needed for particular heating and cooling systems at the time he or she runs the main MEB program.

Energy balance models of greenhouses have been published by Businger (*1963*), Walker (*1965*), Selcuk (*1970*), Takakura et al. (*1971*), Iwakiri (*1971*), Kimball (*1973*), Garzoli and Blackwell (*1971*, *1973*, *1981*), Maher and O'Flaherty (*1973*), Olszewski and Trezek (*1976*), Takami and Uchijima (*1977*), Froehlich et al. (*1979*), Landsberg et al. (*1979*), Kindelan (*1980*), Silveston et al. (*1980*), van Bavel et al. (*1981*), Duncan et al. (*1981*), Chandra et al. (*1981*), Avissar and Mahrer (*1982*), and Glaub and Trezek (*1981*). These models differ greatly in complexity, but even the more complex ones were not developed with the objective to allow their easy coupling to energy-related devices, particularly devices which may also be complex.

In about 1976 I began to add cooling tower and water tank models to my first greenhouse model (Kimball *1973*). I soon realized that a method was needed to easily couple and uncouple these new models from the greenhouse model. Fortunately, at about this time, Klein et al. (*1975*, *1976*) published their transient simulation program called TRNSYS. The TRNSYS program consisted of a main executive FORTRAN program and a set of subroutines. Each subroutine modeled a particular device, such as a solar collector, thermostat, and pump. The program was highly versatile because the user could specify at run time the devices he or she wished to include in a particular run and how they were to be connected to each other (wire, pipes). The main program kept track of the interconnections and iterated and tested for convergence.

In spite of these virtues, I could not use TRNSYS directly because it was too big to fit the USWCL minicomputer (32K memory). However, because the actual modeling was done in subroutines, the main program was relatively small. This feature made it possible to write the MEB program, which incorporates TRNSYS concepts. It differs from TRNSYS first by being "lean" and secondly by having all the subroutines stored as overlays on a disk storage device. This modular organization allows a portion of computer memory to be dedicated to the main program and the remainder to be used for subroutine modules. The main program can call in subroutine modules from the disk. Many devices can be included in a simulation, but the subroutine for only one device needs to be in memory at one time.

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Another difference from TRNSYS is that most of the subroutines included with MEB handle flows of latent energy. Klein et al. were primarily interested in solar heating applications with sensible energy exchange. The necessary fluid stream information included only temperature and mass flow rate. However, in greenhouses and evaporative cooling devices, much of the energy moves as water vapor or latent heat. Therefore, the fluid stream information for these devices includes humidity ratio in addition to temperature and mass flow rate. Another, minor, difference from TRNSYS involves the philosophy of simulating discrete on-off control devices such as thermostats. If the device switches at a set point, under some conditions the heater or other device controlled by the thermostat will be turned off and on for successive iterations with no convergence. The solution used by TRNSYS is to "stick" the thermostat in one position or the other after a few iterations. In MEB the type 4 and type 22 thermostats model control devices as continuous rather than discrete devices. The temperature (or other input variable) is compared with the set point specified by the user. Values of the deviation from the set point of the control variable from previous iterations are used to compute a new corrected value of the control variable with a Newton-type iteration equation. Because the output from the MEB thermostat varies continuously from 0 to 1, the output of pumps, heaters, and other on-off devices can be only a portion of their given capacity. This corresponds to the average of a real situation in which a device is cycled on and off every few minutes. Equally important, stable simulation is produced.

The overall program organization and use is described in the next section. Then, detailed descriptions of each device submodel are given, followed by some specific numerical examples. Nomenclature and file names are listed in appendixes A and B for the actual program listings provided in appendix C. Next, some convenient coding forms are provided in appendix D, followed finally by detailed lists of codes for all the devices in appendix E.

Individual Devices

The MEB program is organized around subroutines which simulate the performance of various types of energy-related devices. To simulate the performance of an individual device at a particular time, each subroutine requires various pieces of information. Some information normally varies during the course of a simulation (such as outdoor air temperature) and is supplied to the subroutine as *inputs*. Other information normally does not vary during the course of a single simulation but needs to be varied from one simulation to another (such as fan capacity), and this information is supplied as *parameters*. The simulation subroutines modify the inputs or generate new information, and these are returned as *outputs*. The parameters, inputs, and outputs are all numbered sequentially for identification.

For example, one device is a type 18 evaporative air cooler, which is illustrated in figure 1 and described in detail in the "Individual Models of Devices." Inputs 1 through 5 are T_{di}, the entering dry bulb temperature (°C); M_i, the entering mass flow rate (kg/s) (this input is unused); T_{WB}, the entering wet bulb temperature (°C); γ, a control variable from a thermostat or similar device; and P, the barometric pressure. Parameters 1 and 2 are M_{max}, the maximum mass flow rate the blower in the cooler can produce, and η, the saturation efficiency. The type 18 cooler computes outputs 1, 2, 3, and 4: T_{do}, the exit dry bulb temperature (°C) computed from T_{di}, T_{WB}, and η; M_o, the exit mass flow rate (kg/s) computed as the product of M_{max} and γ; W_o, the exit humidity ratio (kg H_2O/kg air) computed from T_{do}, T_{WB}, and P; and E, the evaporation rate (kg/s) computed from T_{di}, T_{WB}, P, M_o, and W_o.

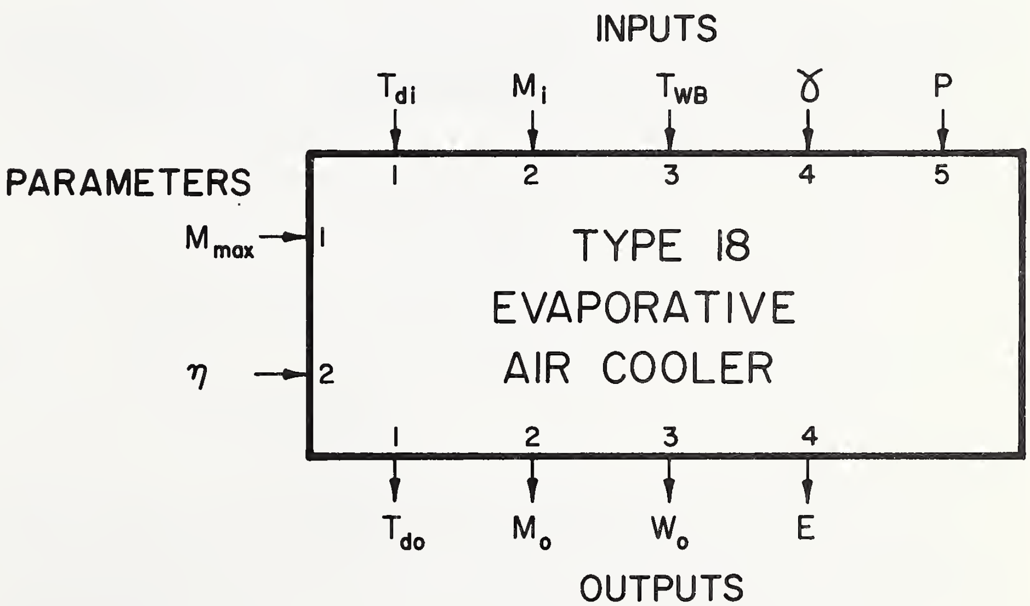

Figure 1.
Functional diagram of a type 18 evaporative air cooler.

Building a System

The MEB program is designed to facilitate connecting individual devices like the type 16 heater into a complete energy system. For example, figure 2 shows eight devices connected together to form a conventional greenhouse with a heater. The type 15 greenhouse has a built-in evaporative cooler. The type 22 multistage thermostat controls the heater and the evaporative cooler, based on the greenhouse air temperature. Three of the devices are conceptual rather than physical. The type 1 reader reads weather data for each time step. The type 3 printer writes the desired output data into a disk file or printer. The type 2 integrator integrates its inputs by the

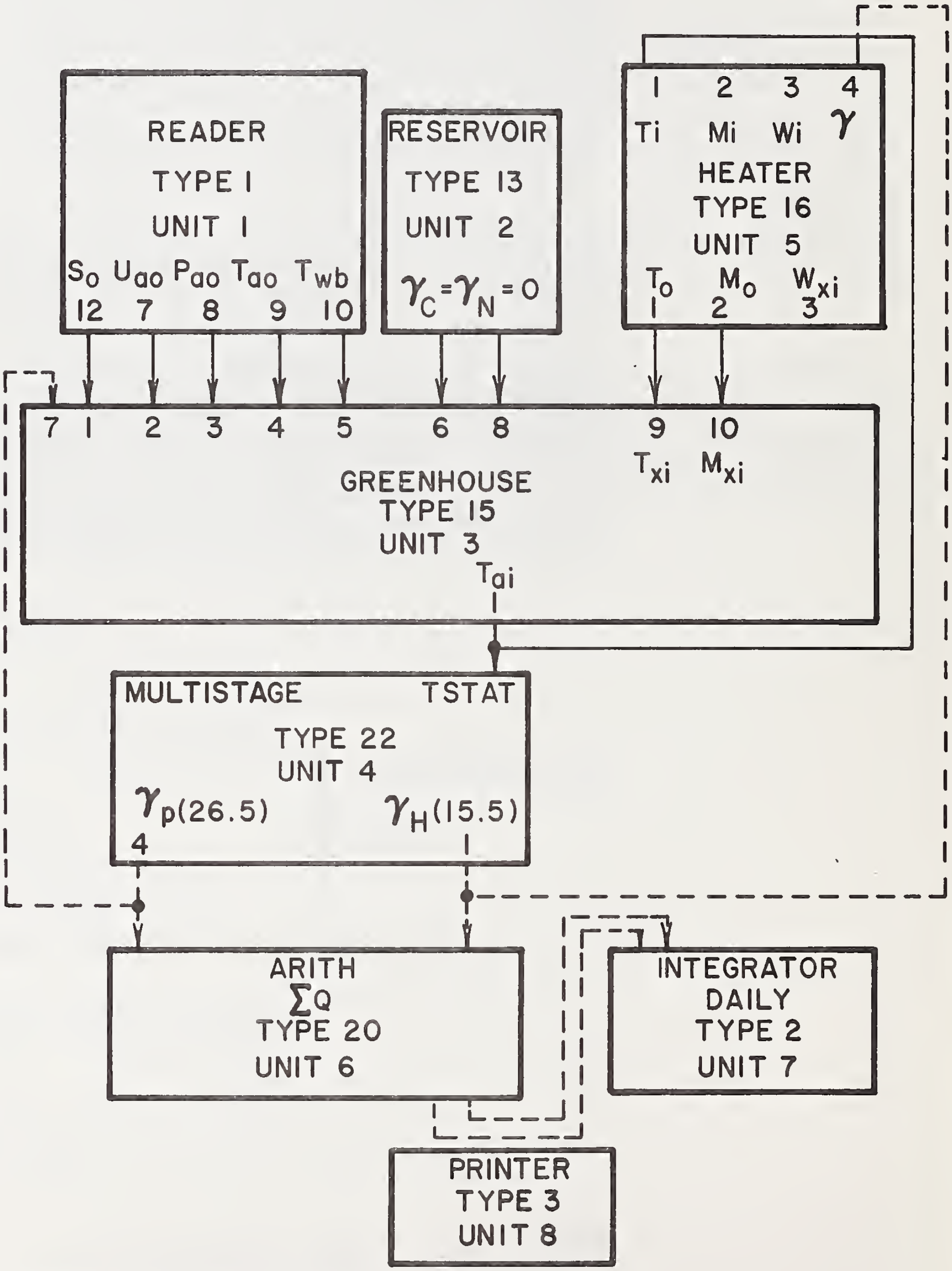

Figure 2.
Information flow diagram for a conventional greenhouse illustrating how eight individual device models are connected to form a complete system.

trapezoid rule. In the example, the two thermostat outputs are being integrated with time, which yields the total operating times of the heater and the evaporative cooler. Then, knowing the power ratings of these devices, their operating expenses are obtained.

Every subroutine model is assigned a *type* number at the time it is incorporated into MEB. The type number is the index to information stored in MEB about the number of parameters, inputs, and so forth, for each subroutine. The procedure for adding new subroutines will be discussed in a later section.

Each subroutine in figure 2 also has a *unit* number, which is chosen by the user at the time each simulation is performed. The unit numbers determine the order in which the various subroutine models are to be called. The unit numbers can be assigned in any order but, to speed convergence, should be in the primary direction of information flow. In figure 2, for example, the reader is numbered first and the printer last. Also, note the logical direction of information flow in the greenhouse-thermostat-heater loop.

Figure 2 is simplified so that only the most important information flows are shown. A type 1 reader actually has 23 outputs, and a type 15 greenhouse has 8 or more inputs and 6 outputs, as described in "Individual Models and Devices" and appendix E. When building a system, it is helpful to construct a diagram like figure 2 to visualize the information flow, even if some of the lesser information flows are omitted to reduce clutter. For the complicated devices, code sheets must be used to assign each input to the output of some device. Because the devices are FORTRAN subroutines, every input must be connected to some output except for a few special cases. The outputs, on the other hand, can dangle and do not have to be connected to another input.

Integration of Differential Equations

The performance of most devices can be modeled by algebraic equations (linear and nonlinear), and these are easily handled by MEB. Some devices, particularly those that store energy, are modeled by differential equations which must be integrated with time. For example,

$$\frac{dT}{dt} = \frac{K}{C}(T_g - T)$$

where T = temperature of a soil layer
t = time
K = thermal conductance
C = heat capacity
T_g = soil surface temperature

The integration required is quite different from the simple accumulation done by a type 2 integrator. Following Klein et al. (*1976*), MEB can integrate such an equation by using a modified Euler method. It is a predictor-corrector method using the Euler method for predicting step and the trapezoid rule for correcting them. At time t, the values of the dependent variables are predicted using their values and the value of their derivatives from the previous time step:

$$T_p = T_o + \Delta t(dT/dt)_o$$

where T_p = predicted value of a dependent variable at time t
T_o = value of the dependent variable at time $t-\Delta t$
Δt = increment of time between simulation times
$(dT/dt)_o$ = value of the derivative at time $t-\Delta t$

Then, the derivatives dT/dt are predicted as a function of t, T_p, and the solutions to the algebraic equations in the models:

$$\frac{dT}{dt}=f(T_p, \text{algebraic equations})$$

The corrected values of the dependent variables, T_c, are next obtained by applying the trapezoid rule:

$$T_c=T_o+\Delta t[(dT/dt)_o+(dT/dt)]/2$$

A test for convergence is then made. If

$$\frac{|T_c-T_p|}{T_c}<\epsilon$$

where ϵ is the error tolerance, then convergence is achieved, and $T=T_c$. Otherwise, T_c is set equal to T_p and the last two equations are repeated. The procedure is repeated until convergence is attained or until the maximum allowable number of iterations is exceeded.

This integration method is unstable if the value of the time step chosen by the user is too large. The maximum stable time step can be estimated from the coefficients in the differential equation. For equations of the form

$$C\frac{dT}{dt}=K_1(T-A)+K_2(T-B)+G$$

where C is a thermal capacitance (J/°C)
T is temperature (°C)
t is time (s)
K_1, K_2 are thermal conductances (J/s°C)
A, B, C are constants (with respect to this equation)

this integration algorithm is stable if

$$\Delta t<\frac{C}{K_1+K_2}$$

Smaller time steps than this maximum should also be tested to see whether significantly different results are obtained. If they are obtained, the smaller time step should be used because the corresponding values are more accurate.

Overall Program Organization

An overall picture of the computational sequence of the MEB program is shown in figure 3. First the program reads run information supplied by the user (format to be discussed later). This includes the starting time, the time step, the number of times simulations are to be done, and the number of units. Then, for each unit in turn the

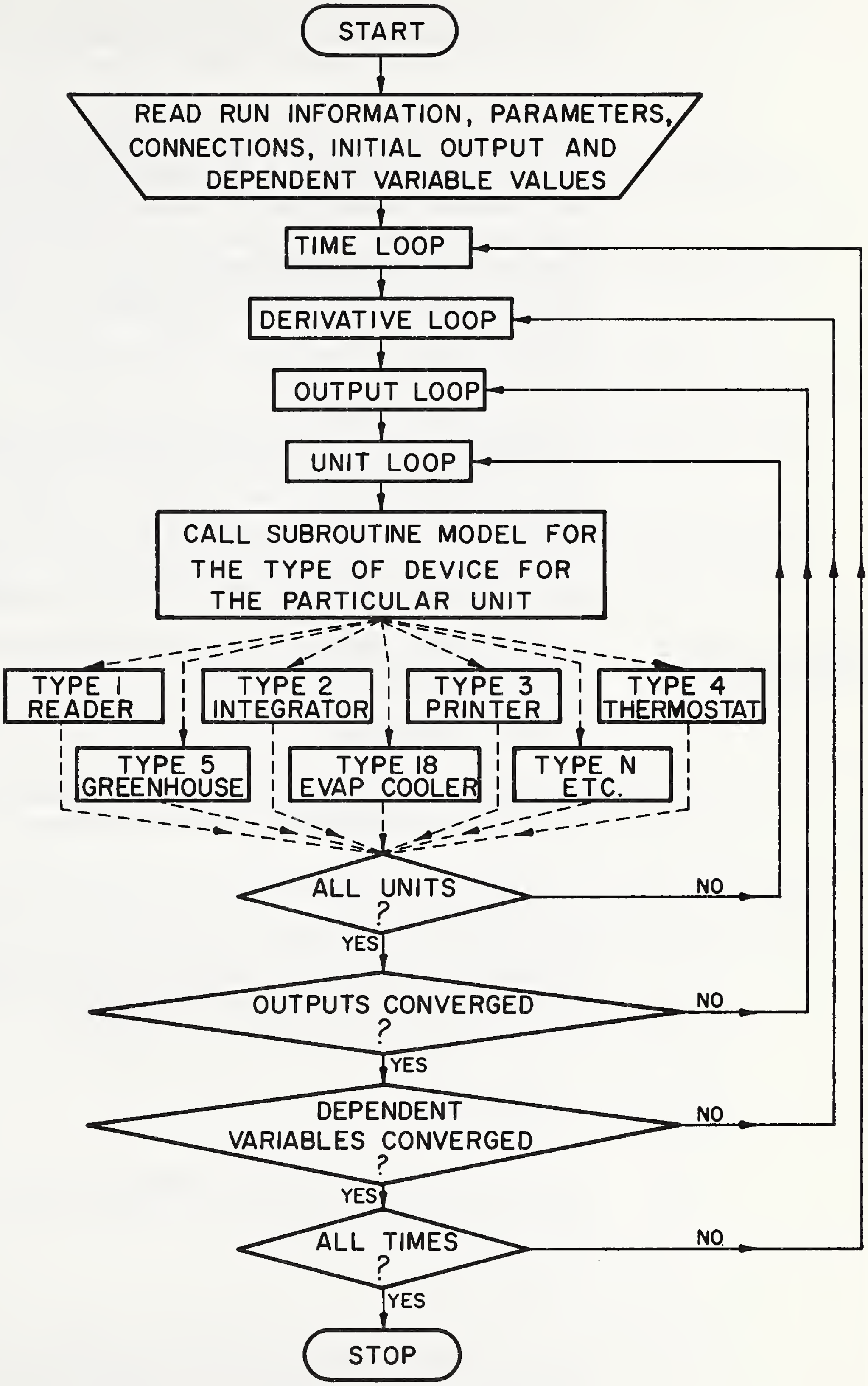

Figure 3.
Overall flow diagram of the modular energy balance (MEB) program.

program reads the parameters for that unit, the unit and output numbers of the other units connected to the inputs of that unit, the initial values of outputs for that unit, and the initial values of dependent variables requiring integration for that unit.

Once the initialization is completed, the program sets up four major computational loops. As shown in figure 3, the outer loop is the time loop that steps the program through the desired simulation times. The next loop is the derivative loop. It integrates differential equations using the method discussed in the previous section. Inside the derivative loop is the output loop. This loop solves the algebraic equations of the component models and iterates until the outputs no longer change. In the innermost loop, each unit is considered in sequence. The subroutine model corresponding to the type of each unit is called. If the inputs to a particular unit haven't changed since the previous iteration, that unit is skipped to save computation time.

The advantages of the modular structure can be seen in figure 3. The main program is relatively small, but several of the more than 20 type subroutines are fairly large. The total package requires about 100,000 words of storage, more than available from minicomputers. Using disk overlays, however, only one type subroutine needs to be in memory at a time. If the type subroutine for a particular unit is not in memory, the overlay module containing that subroutine is loaded into memory from the disk as needed. Details of overlay commands are discussed in a later section.

Individual Subroutine Models of Devices

The first line of an individual subroutine model of a device will simply be the subroutine statement with a name, that is,

```
SUBROUTINE DEVICE
```

Information is passed from main program to the subroutines and back again by variables stored in COMMON. The first COMMON statement is

```
COMMON TIME, XIN(40), OUTI(80), TI(10), DTDTI(10), PARI(99)
```

Before calling an individual subroutine, the main program stores the inputs and the parameters for it in the XIN ( ) and PARI ( ) arrays. Thus, if the first parameter is an area and the first input is an air inlet temperature, the subroutine would probably have statements like the following near its beginning:

```
AREA = PARI(1)
TAI = XIN(1)
```

The outputs are returned to the main program in the OUTI ( ) array; so if the first output is an air outlet temperature, the subroutine would probably have a statement like the following near its end:

```
OUTI(1) = TAO
```

Similarly, for those devices having derivatives, predicted (and corrected) values of dependent variables are supplied to the subroutine in the TI( ) array, and the values of the derivatives must be returned in the DTDTI( ) array. Thus, somewhere in the subroutine, a statement such as the following must appear:

```
DTDTI(1) = A * (B - C) * TI(1)
```

If the value of the dependent variable is also desired as an output, a statement such as the following can be included in the subroutine:

```
OUTI(3) = TI(2)
```

Note that the output number does not have to be the same as the dependent variable number but that the derivative numbers and the dependent variable numbers must correspond.

The value of time is also available to the subroutine from the first COMMON line. If needed, the following second COMMON line can be included:

```
COMMON ETOL, ITMAX, NTIMES, FTRACE, STRACE, DELT, HDELT
```

This provides the value of the error tolerance, maximum number of iterations, total number of simulation times, time of first trace, time to stop trace, the time increment (seconds) and half the time increment, respectively.

Variable device (or logical unit) names for the MEB input device, the type 1 reader input, the MEB output file, and the user's terminal are stored in labeled COMMON called FILES:

```
COMMON/FILES/INDATA, KLMIT, KOUT, LUTERM
```

If a user wishes to write a message and print some data using the trace feature, a statement like the following could be included:

```
    IF (TIME.GE.FTRACE.AND.TIME.LE.STRACE)WRITE(KOUT, 123) T1, T2
123 FORMAT (1H , "INLET AND OUTLET TEMPS ARE", 2E13.6)
```

If the subroutine must store additional information from one call to the next, labeled COMMON statements can be used. Such a statement in the main program and another in the subroutine will store the information even if the subroutine is overlaid by another between calls.

Run Information File

The MEB program first reads information about each simulation run from the run information file called MEBDI (modular energy balance data in). Coding forms for this file are presented in appendix D so that they may be photocopied for use. The data are separated by commas in a free-format style. If there are too many values to fit on a particular line, a slash (/) may be used instead of a comma at the end of the line in order to continue on the next line. The file structure and the free-format style are compatible with Hewlett-Packard Company equipment. In subroutine INIT, which reads file MEBDI, an asterisk (*) is used in place of format statement numbers to indicate free format. Alternate instructions for Data General Corporation equipment are available from the author upon request. Other users have versions running on a Digital Equipment Corporation VAX computer.

The first line in the coding form for file MEBDI (appendix D) provides for entering a title of up to 80 alphanumeric characters (except no commas are allowed). It will be printed in the output file as a label for the particular run. The second line must contain the file name or device code from which weather data are to be read by the type 1 reader. Similarly, the third line must be the file name or device code where the output is to be written. For exmple, if a test of the type 15 greenhouse were to be made using 11 December 1980 weather data from a file called D012 and the output were to go to a line printer whose device code is 6, the first three lines of file MEBDI could be

```
TYPE 15 SIMPLE GREENHOUSE TEST WITH 11DEC80 DATA
D012
6
```

The fourth line of file MEBDI must contain the actual year (last two digits), month, day, and hour (fractional hours permitted) corresponding to the initial simulation time (TIME = 0). These data are used by the type 1 reader to select data desired for the first simulation time. Thus, the user can skip data at the beginning of the file, if desired, in order to begin the simulation with data obtained later than at time zero. The fourth line must also contain the time step (hours), the number of times the simulation is to be done, and time of the first trace and the time to stop the trace. When the simulation time is within the band defined by the first and last trace times, MEB will print the inputs, outputs, and derivatives for every iteration. Using this trace is helpful for debugging new device subroutines and for finding connection errors when building complicated systems. However, the output may be voluminous, so the user should be prepared to interrupt the program after just a few iterations.

The trace times are elapsed times in hours (can be fractional) with respect to the initial time (TIME = 0.0). To trace the initial hour through the fourth hour, the first trace is set equal to 0.0 and the last trace equal to 4.0. For no trace, the user should set both to −1.0 or a similar nontime. For example, suppose total daily time for operating a heater is needed in the type 15 greenhouse test. The test could start at midnight of 10 December, which is time zero for 11 December, and the simulation would run until midnight of 11 December. This simulation will cover 24 hours, and using data at 1.0-hour intervals, 25 lines of weather data will be required. The reason

for the one extra set of observations is that at each time, MEB only computes rates, which then have to be integrated by the type 2 integrator between time steps. Therefore, every simulation involving integration must include at least one time beyond the initial zero time. Now, further suppose that a trace is needed for zero time only. The fourth line of the MEBDI file would be

```
80, 12, 11, 0.0, 1.0, 25, 0.0, 0.0
```

The fifth line in the MEBDI file is the number of units in the system. Then, for each unit in sequence the file must contain the device type, parameters, inputs, initial output values, and initial values of the dependent variables in differential equations, which are called TYPE, PAR, IN, OUT, and T, respectively, on the coding form for file MEBDI. For the parameters line, the user simply refers to the code sheet for the particular device type (appendix E) and supplies values for each parameter for this particular simulation run. Some devices have a variable total number of parameters, and their first parameter is the total number of parameters. For these devices, the first parameter must be separated from the second by a carriage return rather than a comma so that it appears on a line by itself. For example, the first two lines of information about a type 16 heater with maximum heating capacity of 7,000 W, mass flow rate of 0.26 kg/s, and water vapor generation rate of 0.0 kg/s could be

```
16
7000, 0.26, 0.0
```

The computer ignores extra values at the ends of lines, so the first two lines could also contain some extra information for the user's benefit, such as

```
16, ELECTRIC HEATER WITH FAN (UNIT 5)
7000, 0.26, 0.0
```

The inputs line is more complicated. Each input consists of a pair of integer numbers (but all numbers must be separated by commas or slash-carriage returns). The first and second numbers in each pair are, respectively, the unit number and the output number of the device connected to that input. For example, consider the inputs for the type 16 heater, which is unit 5, in figure 2. The inputs are 1, the dry bulb temperature; 2, mass flow rate; 3, humidity ratio of the entering air stream; and 4, control variable. The dry bulb temperature is output 1 from the type 15 greenhouse, which is unit 3. The control variable is output 1 from the type 22 thermostat, which is unit 4. The mass flow rate for a type 16 heater is somewhat unusual because the heater contains its own fan and the output mass flow rate does not depend on the input flow rate. Consequently, input 2 can be connected to any output, even one from its own unit. Neither the type 15 greenhouse nor any other device in this system uses humidity ratio information. Therefore, paramter 3 for this heater, which is the maximum rate of water vapor addition, should be zero, and input 3 can be connected to any output, even one from its own unit. Then, the input line for this heater could be

```
3,1, 5,2, 5,3, 4,1
```

The outputs line consists of initial values of the outputs to be used for the first iteration. For nonlooping information flow, these initial guesses are not used. For example,

in figure 2, the initial outputs of unit 1, which is a type 1 reader, can all be 1 or zero or whatever. Because unit 1 is called first, these initial values will have been replaced before subsequent units are called. These values are important, however, when there are loops in the connections; so the inputs of some unit are connected to the ouputs of another device with a higher unit number. In figure 2, inputs 9 and 10 of the type 15 greenhouse, which is unit 3, come from the outputs 1 and 2 of the type 16 heater, which is unit 5. Therefore, a good guess should be made of the initial outputs 1 and 2 of the heater; but the other unused outputs can be initialized to anything. For example, if time zero is midnight in December, the heater is probably operating near capacity. A 7,000 W heater with a 0.26 kg/s fan will increase the temperature of an air stream by about 27°C; so if the air entering the heater from the type 15 greenhouse is about 15°C, the air will exit the heater at about 42°C. Thus, the initial outputs line for this type 16 heater might be

42, 0.26, 0.

The derivatives or T line consists of initial values for the dependent variables that appear in differential equations. All of these values are used, so good data are needed. However, the user sometimes may not know what the initial temperature of a device, such as a type 11 tank of water, really would be under actual operating conditions. For many of these cases, a guess can be made and then a preliminary run can be made using weather data for the previous day repetitively for several diurnal cycles. At the end of the preliminary run, the guess should have approached a value representative of the weather for the previous day, and the user can then use this value for the actual simulation run.

Some types of devices do not have any inputs, and others lack outputs or derivatives (for example, the type 16 heater, which has no derivatives). For such devices, the particular data line is simply omitted. The type 3 printer has an extra complication. After the last input for it, the next line must be a string of alphanumeric labels, with a blank (or some character) separating the labels. These labels will be printed beside each value printed by the printer, and each must be no more than three characters long. There must be the same number of labels as inputs. If there are too many labels to fit on one line, they can be continued on the next line; but a carriage return (no slash) must come *between* labels at the end of the first line.

Overlays and Program Segments

Because the size of the main program plus all the subroutines exceeds the 32K words of memory accessible to an individual user of a 16-bit-word minicomputer, the program was segmented into smaller modules. Only the main program plus another module containing one or more of the subroutines need to be in the computer at the same time. The other segments or modules are stored on the disk, and they are called into memory as needed, overlaying a previous segment. The method to be described is specific for a Hewlett-Packard computer with an RTE-IVB operating system. However, the overlay feature has been implemented by several manufacturers of minicomputers with disk operating systems, and the general concepts apply. Users of large mainframe computers or those with "virtual" memory do not need overlays, and they may delete statements which pertain to the overlays. These statements are set apart by COVOVOV comment lines in the program listings (appendix C).

The version of MEB presented in appendix C utilizes four segments which are named MEBV0, MEBV1, MEBV2, and MEBV3, using the four DATA statements near

the beginning of the main program. The ASSIGN 100 TO INSTN statement which immediately follows tells the Hewlett-Packard RTE-IVB system what instruction to execute after loading the initial program segment. The segment is loaded by calling a system subroutine:

```
CALL SEGLD (MEBV0, IERR, INSTN)
```

where IERR is a error code for system problems encountered loading the segment. If an error return is made, the first statement executed is the next statement after the CALL SEGLD (   ).

Each subroutine could have been made a segment. However, many of the subroutines that model simple devices are short, and there is room for several of them in memory in addition to the main program. To avoid unnecessary overlaying, several subroutines can be grouped into one segment so long as the total size of the segment plus main program does not exceed user available memory. If a user plans to repetitively simulate a particlular greenhouse system, the subroutines required by that system should be grouped together into as few segments as possible using the editor. The variable "IV" is used by the main program to check which segment is in memory; and if the needed subroutine is already in memory, no segment load call is made.

The user must tell the main program which subroutines are in which segment. This is done at the end of the BLOCK DATA subprogram, where the IUSEG array is initialized with a DATA statement. In the version presented in appendix C, ISEG(1) = 1, which means that the type 1 reader subroutine is in segment 1. Similarly, IUSEG(2) = 1, so the type 2 integrator subroutine is also in segment 1. The first four device subroutines are all in segment 1; and then IUSEG(5) = 2, so the type 5 greenhouse subroutine is in segment 2, and so forth. Note that the large subroutine for the type 14 complicated greenhouse is in segment 3 all by itself.

Each segment requires a short main program at its beginning which is

```
PROGRAM MEBV_(5)
DIMENSION IPAR(5)
CALL RMPAR (IPAR)
INSTN = IPAR(1)
GOTO INSTN
END
```

The blank in the program segment name should be assigned the segment number. Then the (5) and the other statements provide a cumbersome but workable path back to the main program. This provision is needed because after a segment is loaded, the RTE-IVB operating system starts executing the first statement of the segment.

After a user has segmented the subroutines, each segment and the main program must be compiled using the command

```
FTN4X, name, 6, -
```

where name is the file name of the main program or particular segment. Hewlett-Packard uses the convention that FORTRAN source files should start with an &; so the names of the main program and segments are &MEBM, &MEBV0, &MEBV1,

&MEBV2, and &MEBV3. The FORTRAN compiler replaces the & with a % to name the relocatable binary files. These % files are then loaded using the command

```
LOADR, MEBLD
```

where MEBLD is a file containing the following commands:

```
: OP, LB
: RE, %MEBM
: SEA
: RE, %MEBV0
: SEA
: RE, %MEBV1
: SEA
: RE, %MEBV2
: SEA
: RE, %MEBV3
: SEA
```

The OP, LB specifies a large background program. The RE loads the main program or segment named following the comma, and the SEA searches all libraries for any needed routines.

To start the MEB program, the user issues the command

```
RU, MEBM
```

from a terminal, where MEBM is the file name of the main program. Of course, the MEBDI and weather data files must be ready before the program run is started.

Incorporating New Component Subroutines

Several changes need to be made to the main program, to the BLOCK DATA MEBBD subprogram, and to subroutine INIT when a new component subroutine model is added to MEB. For devices with a constant number of parameters, inputs, outputs, and derivatives, the changes are straightforward, as follows:

1. In the main program (appendix C), find the computed GOTO statement. If the new device is a type 25, add a ,25 to this statement.

2. Below the computed GOTO, add two statemments similar to those already there for other devices. If the new type 25 model is in subroutine DVICE, the two statements would be

```
25 CALL DVICE
   GOTO 310
```

3. Referring to the listing for BLOCK DATA MEBBD in appendix C, find the DATA statement for initializing the KARTYP array, which stores the characteristics of the various types of devices. Then, if the new device is a type 25, set the 25th element in the P rows to the number of parameters, the 25th element in the I rows to the number of inputs, the 25th element in the O rows to the number of outputs, and the 25th element of the D rows to the number of derivatives.

4. Similarly, find the DATA statement in BLOCK DATA MEBBD for initializing the IUSEG array, which indicates which segment each subroutine is in. If the new type 25 device is to be in segment 2, set the 25th element of the S rows to 2.

5. In SUBROUTINE INIT, find the computed GOTO statement. As was done in the main program, add a ,25 to the statement for a type 25 device.

6. Below the computed GOTO, add three statements similar to those already there for other devices. These statements will write a label in the output for this device. Typical statements are

```
 25 WRITE (KOUT, 525) IUNIT
525 FORMAT (/ " UNIT ", I2, " IS A TYPE 25 NEW DEVICE ")
    GOTO 206
```

The above six steps are all that is required to incorporate most new subroutine models. However, some models may have a variable number of inputs, outputs, or derivatives (variable number of parameters will be discussed shortly). For such models, other steps in addition to step 3, are required for initializing the KARTYP array. For example, additional steps are shown in the following discussion of the type 5 greenhouse. This greenhouse can have variable numbers of inputs and outputs because it can be connected to none or several other external devices that add sensible and latent heat to the greenhouse air. It can also have variable numbers of derivatives and outputs becuase it can have a variable number of soil layers. The number of inputs is $14+3^{*}J$, where J is the number of devices. The second parameter is made to be the number of devices, and the number of inputs is computed from this parameter in subroutine INIT. Note the fifth statement after statement 102:

```
IF(KTP.EQ.5)KARTYP(5,2) = 14 + INT(3.*PAR(IPARF + 1)+.1)
```

The two 5's in this statement refer to the type 5. The second subscript of KARTYP has the following code: 1, for parameters; 2, for inputs; 3, for outputs; and 4, for derivatives. For this example, 2 is required. At statement 102, the parameters have already been read into the PAR( ) array, and the first parameter for the unit being considered has the subscript IPARF. Therefore, the number of devices, J, for the type 5 greenhouse, which is its second parameter, is found in PAR(IPARF + 1). Thus, the number of inputs is computed from

```
14 + INT(3.*PAR(IPARF + 1)+.1)
```

where the INT and the .1 convert from real to integer variables.

Similarly, the number of derivatives in the type 5 greenhouse is M, which is its third parameter. The value of M is found in PAR(IPARF + 2) in subroutine INIT. Therefore, the appropriate statement in subroutine INIT for computing the number of derivatives for the type 5 greenhouse is the sixth statement after statement 102:

```
IF(KTP.EQ.5)KARTYP(5,4) = INT(PAR(IPARF + 2)+.1)
```

The number of outputs from the type 5 greenhouse is $22+M+3^*J$. The value of M was just computed and stored in KARTYP(5,4). Therefore, the appropriate statement in subroutine INIT for computing the number of outputs for the type 5 greenhouse is the seventh statement after statement 102:

```
IF(KTP.EQ.5)KARTYP(5,3) =22 + KARTYP(5,4) + INT (3.*PAR(IPARF +1)+.1)
```

Similar statements can be used for other cases, as illustrated by the dozen or so statements following statement 102 in subroutine INIT.

For models that have a variable number of parameters, the KARTYP (,1) array must be initialized by making the first parameter the total number of parameters; and this entry must be put on a line by itself in file MEBDI ahead of the other parameters. Then starting at statement 236 in subroutine INIT, there are statements to read this first line and then to use the value read to determine how many more parameters to read from the next line or lines. To incorporate a new model with variable parameters, a GOTO statement must be added shortly after statement 206 to direct the program to the special reading statements. As can be seen for the type 5 greenhouse, this statement has the form

```
IF(KTP.EQ.5) GOTO 236
```

where the 5 refers to type 5.

Some models may also need to save information from previous iterations. This can be accomplished using a labeled COMMON statement in the subroutine model, main program, BLOCK DATA MEBBD, and subroutine INIT. The variables can be intialized in subroutine INIT as was done for the type 4 thermostat at statement 148 and the type 5 greenhouse at statement 147. Here, variables are being initialized to the initial output values read from the input file. IOUTF is the subscript which references the first output for the unit whose data are being read or initialized.

Type 1 Reader

This subroutine is not a model of a device but, rather, a conveyance for getting weather information (or other time-dependent information). Generally, a type 1 reader will be the first unit of a simulation system. The particular version in this paper reads data generated by a previous DECODER program for National Weather Service CD 144 Airways data. This program is similar to the CLIMAT program and the subroutines SUN, CCF, and SOLAD, described by the ASHRAE Task Group on Energy Requirements for Heating and Cooling (*1975*). The DECODER program reads the NWS tape; performs conversions to SI units on the dewpoint, windspeed, pressure, dry bulb temperature, and wet bulb temperature; and outputs these data along with relative humidity and humidity ratio. The DECODER program also computes total and diffuse solar radiation and angle of incidence on horizontal, vertical, and latitude plus 10-degree surfaces from cloud-cover and sun-angle equations using the model of Kimura and Stephenson (*1969*). In addition, from temperature, vapor pressure, and cloud cover, total sky radiation and 8- to 14-μm sky radiation are computed using the method of Kimball et al. (*1982*). The National Weather Service has recorded data at only 3- or 1-hour intervals, yet many simulations require smaller time steps for integration stability (see "Integration of Differential Equations"). Therefore, the DECODER program also interpolates the weather service data and generates hourly or half-hourly values using the four-point smoothing method of Snyder (*1976*).

The sequential code for the 23 outputs of this version of a type 1 reader is given in appendix E. The particular input format can be seen from inspection of the FORMAT statement in the listing in appendix C.

Type 2 Integrator

Like the reader subroutine, this subroutine is not a model of a particular device (except possibly a watt-hour meter) but, rather, an integrator or accumulator of information with time. Using the trapezoid rule, the inputs are integrated with time, and the computed integrals are the outputs corresponding to the inputs having the same sequence number. Mathematically,

$$Y_i = \int_{t_o}^{t} X_i dt$$

where X_i = ith input, Y_i = ith output, t_o = initial or reset time, t = time of current simulation, and dt = the time increment (seconds). As can be seen from codes in appendix E, the type 2 integrator has three parameters. The first parameter is the number of inputs (and outputs), and the second is the elapsed time (hours) between resetting the accumulators to zero. The third parameter is the unit number of a particular integrator. MEB uses this parameter to keep track of the accumulated values when more than one type 2 integrator are used in a simulation.

Type 3 Printer

As the name implies, this subroutine is not a model of an energy-related device but is simply a conveyance for getting information out of the program that can be read by the user. A type 3 printer can handle up to 40 inputs and has no ouptuts as far as the other components of MEB are concerned. However, as far as the user is concerned, this subroutine outputs the results of the simulation.

As can be seen from the codes in appendix E, a type 3 printer has four parameters. Parameter 1 is the number of inputs to be printed, and parameter 2 is the elapsed time (hours) between printouts. Through parameter 2, the user can control how often the data are printed out, thus obtaining daily rather than hourly values, for instance. Parameter 3 is the number of characters per line of the printer. If parameter 3 is 80 or less, 5 output values will be printed per line; otherwise 8 values will be printed. The format used for each value is 1X,2A2,E12.6, where the 1X produces a space, the 2A2 prints the 3-character label dicussed in "Run Information File", and the E12.6 prints 6 digits in a 12-character-wide exponential field. Parameter 4 is the unit number of a particular printer. MEB uses this information to keep track of the labels when more than one type 3 printer are used in a simulation.

Type 4 Thermostat

The type 4 thermostat compares a temperature (or other variable) given as input 1 with a set point temperature, given as parameter 1, and then computes a control variable whose value ranges from 0.0 to 1.0, as illustrated in figure 4. It also has a differential mode whereby the input variable is computed to be the difference between inputs 1 and 2, $T_1 - T_2$. There are two outputs: output 1 comes on with a temperature decrease for controlling heaters and output 2 comes on with a temperature increase for controlling coolers.

The logic of a real thermostat is simple: it is either on or off. If a real heater is too small to compensate for a cold environment, the heater will be on continuously because the temperature is below the thermostat set point; and under hot environmental conditions, it will be off with the temperature above set point. In the intermediate condition, the thermostat will cycle the heater on and off every few minutes with the temperature close to the set point.

Mathematically, a thermostat can be described as follows:

$$\text{If } T_1 > T_s,\ \gamma_H = 0$$
$$\text{If } T_1 < T_s,\ \gamma_H = 1$$

where γ_H is the output control variable for heaters, T_1 is the input temperature, and T_s is the set point temperature. However, γ_H is poorly defined if $T_1 = T_s$. Use of a model thermostat that relies entirely on the above two statements can result in instability when the capacity of the heater is large enough to maintain temperatures at the set point. Iterative simulation programs like MEB or TRNSYS (Klein et al. *1976*) will turn the heater off on one iteration and, when the resultant temperature is too cold, will turn it back on again for the next. With the heater on full, the temperature becomes too warm, so the thermostat will turn the heater off again. As a result, the program will never converge.

The remedy used by Klein et al. is to "stick" the thermostat in one position or another after a few iterations. This is all right for controlling a small pump on a solar collector, which is supposed to run continuously when the sun is shining and be off when it is not. The ambiguity is limited to a fairly short duration near sunrise and sunset. Generally, however, this remedy can lead to significant errors because the capacity of most heaters and coolers is selected to maintain the temperature of an air conditioned space at a set point for long durations.

A more realistic remedy is used by the type 4 thermostat model presented here. The value of the outputs from the thermostat can vary between 0.0 and 1.0, and all of the

other device models that depend on a thermostatic control are written to make their outputs proportional to the input control variable. Thus, a type 16 heater will have an output of one-half capacity when the control variable equals 0.5. A physical heater that alternates between burning at full capacity and being off every few minutes is modeled as burning continuously but at a fraction of capacity.

One problem arises when using average flow rates. The performance of some devices, such as heat exchangers, changes nonlinearly with flow rate. Therefore, for such devices the actual maximum flow rates must be used. These actual flow rates are the average flow rates divided by the value of the control variable for the particular pump or fan moving the fluid. Once the output temperatures, and so forth, for the actual flow rates are obtained, they can then be linearly scaled using the control variable to obtain average performance.

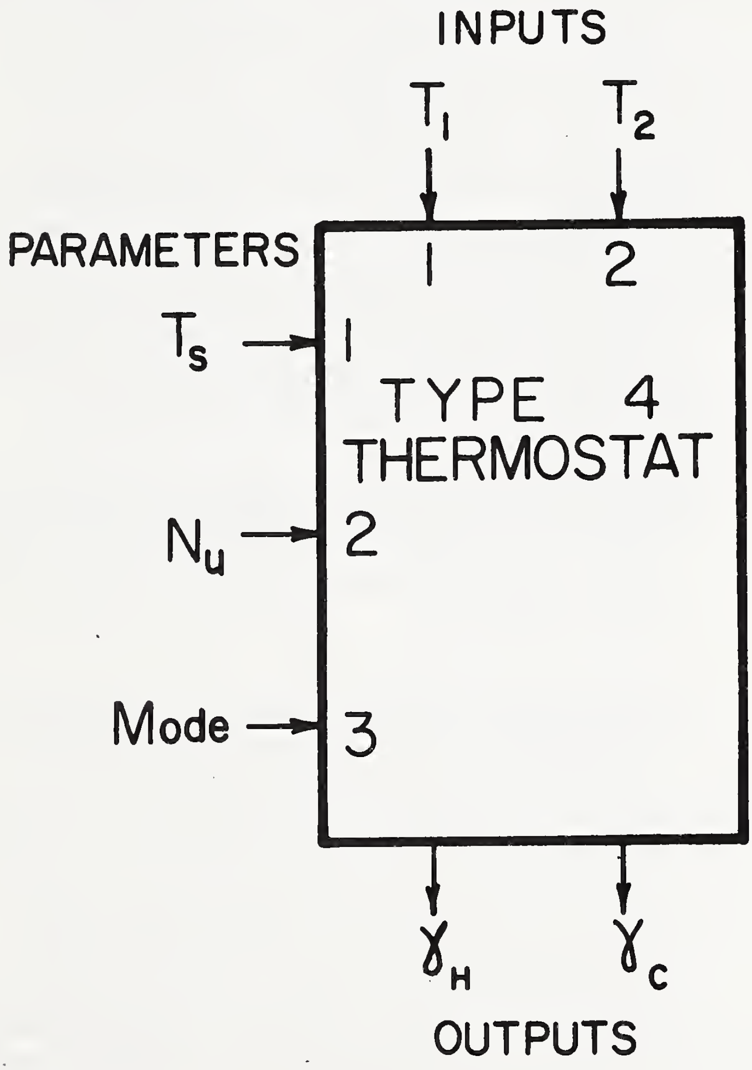

Figure 4.
Functional diagram of a type 4 thermostat. T_s is the set point temperature, N_u is the unit number, Mode is the mode of operation (set = 1 for absolute and = 2 for differential, $T_1 - T_2$ being positive), T_1 is first input variable, T_2 is second input variable (used only when Mode = 2), γ_H is the control variable for controlling heaters ($=1$ when $T_1 < T_s$ *and* $=0$ when $T_1 > T_s$ for absolute mode), and γ_C is the control variable for controlling coolers ($=1-\gamma_H$).

The method used to compute the fractional output for proportional control is a Newton-type iteration. Values of the input temperature and of the thermostat output from previous iterations are stored in labeled COMMON. The change in input temperature resulting from a previous change in the output control variable is used to predict the value of the control variable required to achieve set point temperature. The prediction can be written mathematically as

$$\gamma_i = \gamma_{i-1} - \frac{SF_i}{(F_i - F_{i-1}) / (\gamma_{i-1} - \gamma_{i-2})}$$

where γ = control output variable
F = deviation of input temperature from set point temperature, $T_1 - T_s$. (For differential mode, $F = (T_1 - T_2) - \Delta T_s$)
S = step size
i = current iteration
$i-1$ = previous iteration
$i-2$ = second previous iteration

The step size, S, has been chosen to make the algorithm stable. When S was equal to 1, the predicted control variable often alternated between 0 and 1 on successive iterations, just as the simple on or off model did. However, by making S alternate between 1.0 and 0.1 on successive iterations, big steps are alternated with small steps. As a result, the algorithm is much more stable and generally will converge in about five iterations when the device controlled by the thermostat is the only source of variation in the input temperature to the thermostat.

Type 5 Greenhouse

The type 5 greenhouse is shown schematically in figure 5. Each arrow represents a flux of energy, with the direction of the arrows taken as positive. Included in the analysis are the following fluxes of energy: Solar, S; combined conduction and convection, C; infiltration, I; natural ventilation, N; soil, G; external device, X_j; and evapotranspiration, λE_T.

The type 5 greenhouse model is a compromise between the type 15 simple greenhouse model and the type 14 complicated greenhouse model. The type 15 simple model is similar to the models of Walker (*1965*) and Garzoli and Blackwell (*1971, 1973*) in that only one energy balance is used and evapotranspiration is handled rather crudely. The type 5 greenhouse model raises the level of sophistication by accounting more realistically for water vapor loss and solving for the humidity ratio of the greenhouse air; consequently, it is more like the model of Landsberg, White, and Thorpe (*1979*) or of Seginer and Livne (*1978*). The more sophisticated type 14 complicated greenhouse is similar to the models of Businger (*1963*), Selcuk (*1970*), Takakura, Jordan, and Boyd (*1971*), Iwakiri (*1971*), and Kimball (*1973*) in that individual fluxes of thermal radiation, of sensible and latent heat convection, and of conduction are computed between the soil surface, the vegetation, the greenhouse air, the inside of the greenhouse cover, and the outside of the greenhouse cover. As will be discussed shortly, many of the transfer coefficients in this type 5 model are lumped into a single overall U factor for the conduction and convection loss. Considerable sophistication is retained, however, because the U can be adjusted to account for such factors as thermal radiation through a partially transparent cover, pulling a thermal screen at night, and using a powered circulation fan. Provision is also made for collection of energy from a fluid roof (Damagnez *1976*), and for storage

of energy below the greenhouse in soil (Dale et al. *1979*) or porous concrete (Mears et al. *1977*). This model can simulate either a conventional or an energy-conserving solar greenhouse by proper choice of parameters at run time.

The following notations will be used:

- A area (m^2)
- C convection (W)
- D density (kg/m^3)
- E evapotranspiration (kg/s)
- G conduction in soil or cover (W)
- I infiltration through cracks and interstices (W)
- J number of external devices
- K mass transfer coefficient ($kg/m^2 \cdot s$)
- L leaf area index
- M mass flow rate when subscript affixed (kg/s); number of soil layers when no subscript affixed
- N natural ventilation through ventilators (W)
- P pressure (kPa) or parameter
- S solar radiation (W/m^2)
- T temperature (°C)
- U overall heat transfer coefficient ($W/m^2 \cdot °C$)
- W humidity ratio (kg/kg)
- X energy from external device (W)
- Z soil depth (m)
- b coefficients
- c heat capacity at barometric pressure ($J/kg \cdot °C$)
- h heat transfer coefficient ($W/m^2 \cdot °C$)
- k thermal conductance ($W/m^2 \cdot °C$)
- p water vapor pressure (kPa)
- r resistance ($m^2 s/kg$)
- t time (s)
- u velocity of air movement (m/s) For infiltration, units are millimeters per second; for natural ventilation, greenhouse volumes per hour
- v greenhouse volume (m^3)
- α absorptance
- Δ increment of
- δ slope with respect to temperature (/°C)
- γ control variable
- $\varkappa$ thermal conductivity ($W/m \cdot °C$)
- λ latent heat of vaporization (J/kg)
- ρ reflectance
- τ transmittance

Subscripts are as follows:

- A on an area basis
- B bottom or deep soil
- E latent heat component
- H sensible heat component
- I for infiltration
- N for natural ventilation
- S for solar radiation
- T transpiration
- W for humidity ratio

- ai inside air
- ao outside air
- c cover or roof
- g soil or ground
- i inside
- j index for external device
- m index for soil layers
- n number of the soil layer which can receive a fluid stream from an external device
- o outside
- p for powered air circulation
- v vegetation
- vg average of vegetation and soil
- w wall that does not transmit solar energy or change properties
- x external device
- 0 intercept or control variable equals 0
- 1 refers to the topmost or first member of a series, such as a series of soil layers or coefficients; or refers to the value of the control variable. Higher numbers identify higher members of a series.

Superscripts are as follows:

- * indicates saturated condition
- old from previous iteration

Energy and moisture balance equations

Referring to figure 5, the energy balance equation for the greenhouse air is

$$S_i + \sum_j X_{Hj} + \sum_j X_{Ej} - C_i - I_{cH} - I_{cE} - N_H - N_E - C_w - I_{wH} - I_{wE} - G_1 = 0 \tag{5-1}$$

Similarly, the moisture balance equation for the greenhouse air is

$$\lambda E_T + \sum_j X_{Ej} - I_{cE} - N_E - I_{wE} = 0 \tag{5-2}$$

Note that in figure 5 the evapotranspirational flux is regarded to be entirely within the greenhouse, so it does not enter the energy balance equation. The moisture balance equation, however, is coupled to the energy equation because the vegetation temperature is assumed to be equal to the greenhouse air temperature. The water vapor concentration inside the leaves is assumed to be at saturation for this temperature.

An energy balance equation for the roof, which may contain a solar energy absorbing fluid, is

$$S_c + X_c + C_i - C_o = 0 \tag{5-3}$$

A quasi-steady state is assumed to exist at the time of each simulation. Heat storage in the vegetation and benches is assumed to be negligible. The soil does store energy, however, and differential equations will be presented which describe the flow of energy in the soil and to the soil from external devices. These differential equations are integrated using the method inherent in the main MEB program described previously. Of course, other external devices connected to the greenhouse may also store energy. Such external devices may actually be located inside the greenhouse as long as their only important interaction with the greenhouse is to exchange energy with the greenhouse air.

Refer to the code table in appendix E for parameter and input numbers of variables that must be given to subroutine GH, and bear in mind that T_{ai}, W_{ai}, and T_c are computed by GH as the solution to equations 5–1, 5–2, and 5–3. The individual fluxes in figure 5 and equations 5–1, 5–2, and 5–3 are defined and computed as shown below.

Solar radiation

The solar energy gain inside the greenhouse, S_i, is computed from

$$S_i = A_g S_o \tau_S (1 - \rho_{vg}) \tag{5-4}$$

where τ_S is the transmittance of the greenhouse cover for solar radiation. In a conventional greenhouse, τ_S varies daily and seasonally with sun angle and the orientation of all the cover surfaces. These variations are small compared to the more dramatic effects of a shade cloth or fluid roof (Damagnez *1976*). Therefore, in this model, sun angle effects are ignored and average daily values of τ_S are used. For most greenhouses, the solar energy entering the roof is predominant because the solar energy entering a wall toward the sun is partially offset by that leaving the op-

posite wall; so the area used in equation 5–4 is the soil area, A_g. If a user wishes to simulate a greenhouse with a reflective north wall, he or she can make τ_S greater than 1.0, in effect, increasing the solar energy collection area.

The effects of changing the greenhouse cover material, as with the shade cloth or fluid roof, are handled by changing τ_S in response to two control variables, γ_f and γ_c (inputs 7 and 8, appendix E), which vary from 0 to 1 and can be the outputs of a type 4 thermostat, type 12 clock, or similar device. The transmittance is computed from

$$\tau_S = (1-\gamma_f)(1-\gamma_c)\tau_{S00} + (1-\gamma_f)\gamma_c\tau_{S01}$$
$$+ \gamma_f(1-\gamma_c)\tau_{S10} + \gamma_f\gamma_c\tau_{S11} \tag{5–5}$$

where τ_{S00} is the solar transmittance when there is no fluid in the roof ($\gamma_f = 0$) and no thermal screen ($\gamma_c = 0$), τ_{S01} is the transmittance with no fluid ($\gamma_f = 0$) and with a screen ($\gamma_c = 1$), τ_{S10} is the transmittance with fluid ($\gamma_f = 1$) and no screen ($\gamma_c = 0$), and finally, τ_{S11} is the transmittance with both fluid and screen ($\gamma_f = \gamma_c = 1$). Referring to appendix E, τ_{S00}, τ_{S01}, τ_{S10} , and τ_{S11} are parameters 15, 16, 17, and 18, respectively.

The ability to change the properties of the cover during a simulation makes the model powerful and versatile but at a price of having to supply many more parameters. However, when modeling a conventional greenhouse, only the value of τ_{S00} must be correct because τ_{S01}, τ_{S10}, and τ_{S11} are not used when $\gamma_c = \gamma_f = 0$. For the case of the fluid roof (Damagnez *1976*), the near infrared portion of the spectrum is selectively absorbed, but this does not affect the energy analysis as long as the proper τ_{S10} and τ_{S11} are used.

The solar energy absorbed in the cover, S_c, is computed from

$$S_c = A_g S_o \alpha_S \tag{5–6}$$

where α_S is the absorptance of the cover for solar radiation. The absorptance is computed from an equation analogous to that for computing τ_S:

$$\alpha_S = (1-\gamma_f)(1-\gamma_c)\alpha_{S00} + (1-\gamma_f)\gamma_c\alpha_{S01}$$
$$+ \gamma_f(1-\gamma_c)\alpha_{S10} + \gamma_f\gamma_c\alpha_{S11} \tag{5–7}$$

where α_{S00}, α_{S01}, α_{S10}, α_{S11} are parameters 19, 20, 21, and 22 (appendix E). Besides accounting for the solar radiation that is absorbed as it first penetrates the greenhouse cover, the absorptance values used must also account for any radiation reflected back from the soil and vegetation and then absorbed in the cover.

Sensible and latent heats from external devices

The total sensible energy and total latent energy added to the greenhouse air from external devices are the sums of the energies added from the individual devices. The temperature, T_{xj}; mass flow rate, M_{xj}; and humidity ratio, W_{xj}; of each *j*th device are

inputs to subroutine GH. Then, the total sensible and latent heats, respectively, are computed from

$$\sum_j X_{Hj} = \sum_j M_{xj} c_a (T_{xj} - T_{ai}) \tag{5-8}$$

$$\sum_j X_{Ej} = \sum_j M_{xj} \lambda (W_{xj} - W_{ai}) \tag{5-9}$$

The heat capacity of humid air at constant pressure, c_a (J/kg• °C), is computed from

$$c_a = 1{,}005 + 1{,}859 W_{ai}^{old} \tag{5-10}$$

where W_{ai}^{old} is the humidity ratio from the previous iteration. The latent heat of vaporization, λ (J/kg), is computed from

$$\lambda = 2.501 \times 10^6 - 2{,}381 T_{ai}^{old} \tag{5-11}$$

Equation 5–11 was fitted to the tabular data in List (*1958*, p. 343).

The sensible heat added to the cover or roof from an external device is computed from

$$X_c = M_{xc} c_c [2(T_{xc} - T_c)] \tag{5-12}$$

where T_{xc} is the temperature of the fluid entering the cover from the external device. The temperature difference, $T_{xc} - T_c$, is multiplied by 2 because it is assumed that the fluid in the roof is not well mixed and that T_c is an average cover temperature halfway across the cover.

Similarly, sensible heat may be added to one, the *n*th soil layer as described by the following equation:

$$X_g = M_{xg} c_{xg} [2(T_{xg} - T_{gn})] \tag{5-13}$$

The layer is specified by the value of *n* in parameter 4 (appendix E). Like T_c, the temperature T_{gn} for the *n*th layer is assumed to be an average temperature halfway across the greenhouse; so the temperature change is multiplied by 2. Equation 5–13 omits any details about the heat transfer between the fluid and soil. Thus, it can be expected to apply to greenhouses in which the contact between the fluid and soil is as good as that between water and gravel in the Rutgers greenhouse (Mears et al. *1977*). For fast-moving air in tubes (Dale et al. *1979*), heat transfer may be slow enough that a more complex equation is required. Also, latent heat transfer is not included.

Convection, conduction, and thermal radiation

Referring to figures 5 and 6, the combined convection and thermal radiation from the greenhouse, air, plants, and soil to the greenhouse cover, C_i, are computed from

$$C_i = A_c U_i (T_{ai} - T_c) \tag{5-14}$$

Similarly, the convection and thermal radiation from the greenhouse cover to the outside, C_o, is computed from

$$C_o = A_c U_o (T_c - T_{ao}) \tag{5-15}$$

This model also provides for the side walls (or perhaps just an insulated north wall) to differ in thermal conductance from the cover or roof; and the combined convection, conduction, and thermal radiation through the walls is computed from

$$C_w = A_w U_w (T_{ai} - T_{ao}) \tag{5-16}$$

The U's in these equations are overall coefficients combining the effects of convection, conduction, and thermal radiation. However, they do not account for the infiltration of air through cracks and interstices around glass panes or doors. This distinction is made because different heat transfer mechanisms are involved. Infiltration involves an actual loss of water from the greenhouse, whereas convection and conduction do not (although transpiration and condensation may move the water around inside the greenhouse). Also, infiltration is more affected by wind-induced pressure differences (Okada and Takakura *1973*) and by the quality of construction, whereas conduction is more influenced by the material used for construction.

The overall heat transfer coefficients for the cover or roof (U_o and U_i) depend on the wind speed, the construction material of the greenhouse, the flow rate of any fluid in

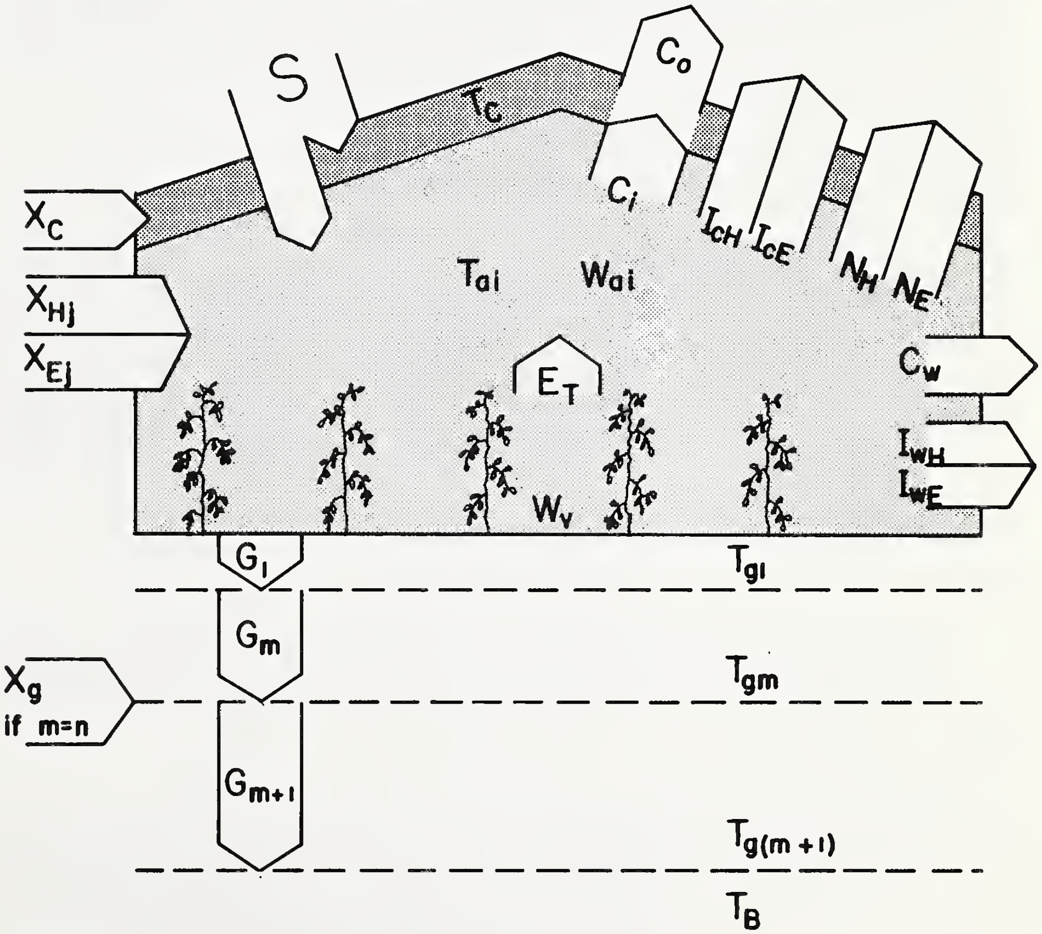

Figure 5.
Schematic illustration of a type 5 greenhouse showing the energy fluxes considered by the type 5 model.

the cover, and the velocity of air movement inside the greenhouse. By adjusting U_o and U_i, conventional greenhouses, fluid roof greenhouses, and greenhouses with thermal screens or other movable insulation can be simulated. The overall heat transfer coefficient for the side walls, (U_w), on the other hand, is assumed to be a constant supplied as parameter 14. Referring to figure 6,

$$U_o = \frac{1}{(1/h_{ao}) + (1/h_{co}) + (1/h_f)} \tag{5–17}$$

$$U_i = \frac{1}{(1/h_{ai}) + (1/h_{ci}) + (1/h_f)} \tag{5–18}$$

The outside heat transfer coefficient, h_{ao} (W/m^2•°C), is a surface conductance (ASHRAE *1972*, p. 347) which includes thermal radiation. It varies with outside wind speed, u_{ao} (m/s):

$$h_{ao} = b_1 + b_2 u_{ao} \tag{5–19}$$

where the coefficients, b_1 and b_2, are parameters 12 and 13, respectively. The inside heat transfer coefficient, h_{ai} (W/m^2•°C), varies with the size of temperature gradients in the greenhouse and with the velocity of air movement provided by any powered circulation fans. For this model the user supplies a daytime (S_o> 10 W/m^2) value,

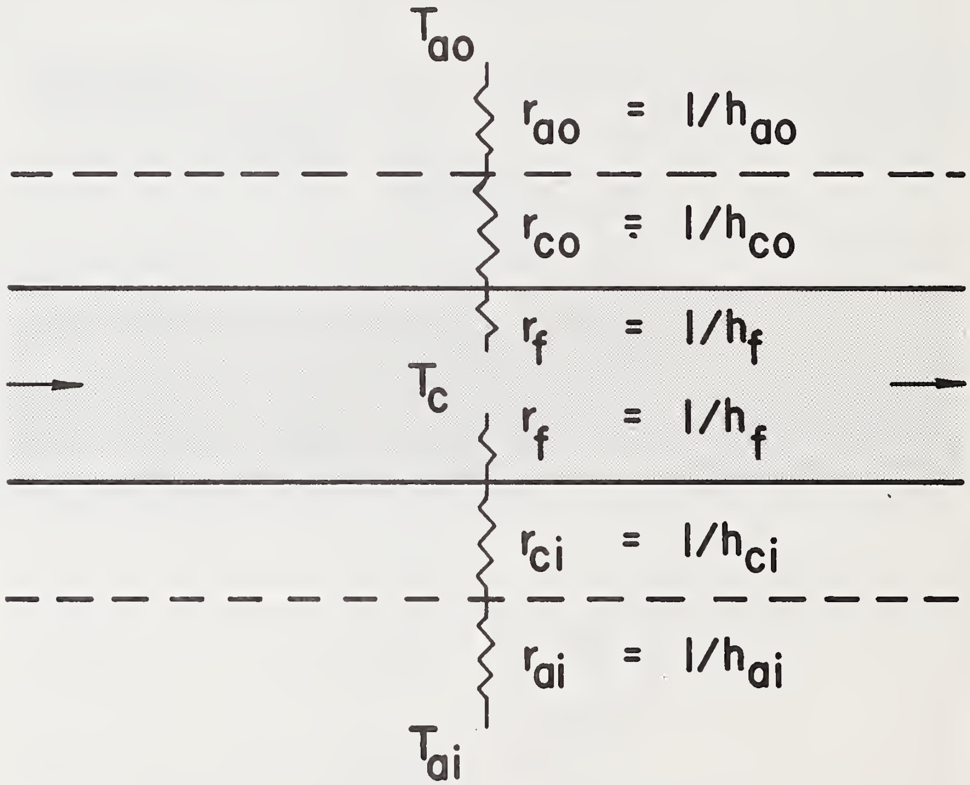

Figure 6.
Schematic diagram of the thermal resistances, *r*, and conductances, *h*, in the cover of a type 5 greenhouse. The r_{ai} and r_{ao} are the inside and outside air film resistances, the r_{ci} and r_{co} are the inside- and outside-cover-material resistances, and the r_f's are the fluid film resistances.

h_{ai0}, for when the fans are off and another value, h_{ai1}, for when they are on, as parameters 23 and 24, respectively. The equation used is

$$h_{ai} = (1 - \gamma_p)h_{ai0} + \gamma_p h_{ai1} \tag{5–20}$$

where γ_p (input 9) is the control variable for the circulation fans.

The fluid heat transfer coefficient, h_f (W/m^2•°C) from the surface of the fluid to inside the fluid is specified by two values, h_{f0} for when no fluid is flowing and h_{f1} for when fluid is flowing, as parameters 25 and 26, respectively. Then,

$$h_f = (1 - \gamma_f)\, h_{f0} + \gamma_f\, h_{f1} \tag{5–21}$$

where γ_f (input 7) is the variable for controlling the fluid flow. By setting h_{f0} equal to a still-air heat transfer coefficient, the user can simulate draining of the fluid. If both h_{f1} and h_{f0} are set equal to very large values, say 10,000 W/m^2•°C, then any temperature change across the fluid becomes insignificant. The model would therefore simulate a greenhouse with no fluid in the roof, that is, one whose cover properties are controlled by h_{ci} and h_{co}, both of which are discussed next.

The thermal conductances h_{co} and h_{ci}, depend on the properties of the greenhouse cover materials. Like τ_S and α_S, they can be changed during a simulation using the control variable γ_c, which allows thermal screens or similar devices to be opened and closed. The conductances are computed from

$$h_{co} = (1 - \gamma_c)h_{co0} + \gamma_c h_{co1} \tag{5–22}$$

$$h_{ci} = (1 - \gamma_c)h_{ci0} + \gamma_c h_{ci1} \tag{5–23}$$

where h_{co0}, h_{co1}, h_{ci0}, and h_{ci1} are parameters 27, 28, 29, and 30, respectively.

Infiltration

The infiltration of sensible energy and latent energy, respectively, by movement of air through cracks and interstices in the cover is computed from

$$I_{cH} = A_c h_{cI} (T_{ai} - T_{ao}) \tag{5–24}$$

$$I_{cE} = A_c \lambda K_{cI} (W_{ai} - W_{ao}) \tag{5–25}$$

where h_{cI} (W/m^2•°C) is the heat transfer coefficient for infiltration and K_{cI} the mass transfer coefficient for infiltration. From the Lewis relation (ASHRAE *1972*, p. 72),

$$K_{cI} = h_{cI}/c_a \tag{5–26}$$

The h_{cI} is computed following Okada and Takakura (*1973*). First, the average velocity of air moving through the whole cover area, u_{cI} (mm/s or (m^3 of air × 10^3/m^2 of cover)/s), is computed:

$$u_{cI} = b_3 u_{ao} + b_4 \sqrt{|T_{ai}^{\text{old}} - T_{ao}|} + b_5 \tag{5–27}$$

Few data are presently available about the coefficients, b's, in equation 5–27. However, it seems reasonable that they all are wall properties and that b_5 also might be affected by an inside circulation fan. Therefore, provision is made for changing the coefficients with the control variables γ_c and γ_p, and they are computed from

$$b_3 = (1-\gamma_c)b_{30} + \gamma_c b_{31} \tag{5–28}$$

$$b_4 = (1-\gamma_c)b_{40} + \gamma_c b_{41} \tag{5–29}$$

$$b_5 = (1-\gamma_c)(1-\gamma_p)b_{500} + (1-\gamma_c)\gamma_p b_{501} + \gamma_c(1-\gamma_p)b_{510} + \gamma_c\gamma_p b_{511} \tag{5–30}$$

where b_{30}, b_{40}, and b_{500} are the values of b_3, b_4, and b_5 corresponding to no thermal screen ($\gamma_c = 0$) and no circulation fan ($\gamma_p = 0$), and so forth. The b's are supplied as parameters 31 through 38, as listed in appendix E. After u_{cl} is computed h_{cl} is obtained from

$$h_{cl} = u_{cl}c_a D_{ao}/1{,}000 \tag{5–31}$$

where the air density, D_{ao}, is computed from the outside temperature and pressure:

$$D_{ao} = P_{ao}/(0.287(T_{ao} + 273.16)) \tag{5–32}$$

The infiltration of sensible energy and latent energy, respectively, through the side wall, doors, and so forth, is computed from

$$I_{wH} = A_w h_{wI}(T_{ai} - T_{ao}) \tag{5–33}$$

$$I_{wE} = A_w \lambda K_{wI}(W_{ai} - W_{ao}) \tag{5–34}$$

where

$$K_{wI} = h_{wI}/c_a \tag{5–35}$$

The velocity of air movement through the wall, u_{wI} (mm/s), is computed from

$$u_{wI} = b_6 u_{ao} + b_7\sqrt{|T_{ai}^{old} - T_{ao}|} + b_8 \tag{5–36}$$

Both b_6 and b_7 are properties of the unchanging wall portion of the greenhouse, but b_8 can be affected by an inside circulation fan. The constants b_6 and b_7 are parameters 39 and 40, and b_8 is computed from

$$b_8 = (1-\gamma_p)b_{80} + \gamma_p b_{81} \tag{5–37}$$

where b_{80} and b_{81} are parameters 41 and 42. After u_{wI} is computed, h_{wI} is obtained from

$$h_{wI} = u_{wI}c_a D_{ao}/1{,}000 \tag{5–38}$$

Natural ventilation

Natural ventilation of both sensible heat and latent heat through ridge, side, or other ventilators is computed from

$$N_H = h_N(T_{ai} - T_{ao}) \tag{5–39}$$

$$N_E = \lambda K_N(W_{ai} - W_{ao}) \tag{5–40}$$

As usual the mass transfer coefficient is computed from the heat transfer coefficient using the Lewis relation (ASHRAE *1972*, p. 72)

$$K_N = h_N / c_a \tag{5–41}$$

To obtain h_N, the rate of air change of the greenhouse is first computed from

$$u_N = (b_9 u_{ao} + b_{10}\sqrt{|T_{ai}^{\text{old}} - T_{ao}|})\gamma_N \tag{5–42}$$

The u_N is number of volumes of greenhouse air exchanged per hour. Comparing equations 5–27 and 5–42, the assumption is made that the outside wind velocity and the temperature difference between the inside and outside air affect infiltration and natural ventilation in a similar functional way. The primary difference is that natural ventilation is used to deliberately lower temperatures whereas infiltration is a consequence of the failure of greenhouse building materials to form a hermetic seal. Experimental measurements of b_9 (parameter 43) and b_{10} (parameter 44) are scarce. Okada and Takakura (*1973*) and Whittle and Lawrence (*1960*) have provided about the only available data. The γ_N (input 10) in equation 5–42 is a control variable that can come from a type 4 thermostat or similar device. As it varies from 0 to 1, it controls the opening and closing of the ventilators.

After u_N is computed, h_N is obtained from

$$h_N = u_N v_{ai} D_{ao} c_a / 3{,}600 \tag{5–43}$$

Soil heat flux

The heat flux at the soil surface is computed from

$$G_1 = A_g k_1(T_{ai} - T_{g1}) \tag{5–44}$$

where k_1 is the thermal conductance of the top soil layer and T_{g1} is the temperature at depth Z_1 at the bottom of the top soil layer. The T_{g1} term is dependent variable 1 from the internal integrator of the main program.

The soil heat flux at the soil surface also depends on the capacity of the soil for storing heat and on the magnitude of the soil heat flux in lower layers. It also depends on the amount of heat supplied to one of the layers, the *n*th, from an external device. The user specifies which layer this may be by the value of *n* as parameter 4. Referring to figure 5, the heat flux for the *m*th layer is defined as

$$G_m = A_g k_m(T_{gm} - T_{g(m-1)}) \tag{5–45}$$

and an energy balance on the mth soil layer yields

$$A_g c_{Am} \frac{dT_{gm}}{dt} = G_{m-1} - G_m + (X_g)_{m=n} \tag{5–46}$$

where the X_g is used only for the nth layer. To use the integration procedure outlined previously, the derivative with time must be solved explicitly. Upon substituting equation 5–45 into equation 5–46 and rearranging the resulting equation, the following is obtained:

$$\frac{dT_{gm}}{dt} = \frac{k_m}{c_{Am}}(T_{g(m-1)} - T_{gm}) - \frac{k_{(m+1)}}{c_{Am}}(T_{gm} - T_{g(m+1)}) + \left(\frac{X_g}{A_g c_{Am}}\right)_{m=n} \tag{5–47}$$

and subroutine GH uses this equation to evaluate the soil temperature derivatives. Again, X_g is used only for the nth layer.

The thermal conductances, k_m (W/m^2·°C) for the various soil layers must be given to the program as parameters 51, 53, 55, and so forth. The user can calculate them from the thermal conductivity, $\varkappa_m$ (W/m·°C) and thickness ΔZ_m (m) of each soil layer as

$$k_m = \varkappa_m / \Delta Z_m \tag{5–48}$$

For the special case of the top soil layer, the k_1 must also account for the surface conductance of the soil-air interface, which is relatively low. Similarly, the area heat capacity, c_{Am} (J/m^2·°C), for the various soil depths must be given to the program as parameters 52, 54, 56, and so forth. The user can calculate them from the specific heat, c_m (J/kg·°C); density, D_m (kg/m^2); and average thickness of the soil layers just above and below the particular depth:

$$c_{Am} = c_m D_m (\Delta Z_m + \Delta Z_{(m+1)})/2 \tag{5–49}$$

For the special case of the top soil layer, all of the top layer is included.

$$c_{A1} = c_1 D_1 (\Delta Z_1 + (\Delta Z_2/2)) \tag{5–50}$$

The temperature is assumed constant at a deep depth. The temperature of this bottom soil, T_B, and its thermal conductance, k_B, must be supplied as parameters 49 and 50.

Remember that the time step used for the simulation and the thermal properties of each soil layer must satisfy the stability criterion (see "Integration of Differential Equations"). For the top layer of soil, usually the thinnest, this implies that Δt must be less than $c_{A1}/(k_1 + k_2)$.

Evapotranspiration

Evaporation is assumed to occur from the substomatal cavities in the leaves of the vegetation and/or from below the soil surface. The rate of evapotranspiration, E_T, (kg/s) is computed from

$$E_T = A_g K_v (W_v - W_{ai}) \tag{5–51}$$

where W_v is the humidity ratio in the substomatal cavities of the vegetation and below the soil surface. The vegetation and the soil surface temperatures are assumed to be relatively close to the greenhouse air temperature, so W_v can be computed as the saturation humidity ratio at T_{ai}. To facilitate later solution of equations, the equation for the saturation humidity ration is linearlized as follows (Kimball *1981*):

$$W_v = W_0 + \delta_w{}^* T_{ai} \qquad (5\text{–}52)$$

where $\delta_w{}^*$ is the slope of the saturation humidity ratio curve. To compute $\delta_w{}^*$, Tetens' equation (Murray *1967*) is used for the saturation vapor pressure, p^* (kPa).

$$p^* = 0.61078\exp(17.2694T/(T+237.30)) \qquad (5\text{–}53)$$

Using the definition for W^* (ASHRAE *1972*, p. 99),

$$W^* = 0.62198p^*/(P_{ao} - p^*) \qquad (5\text{–}54)$$

the slope of the saturation humidity ratio curve is derived:

$$\delta_W{}^* = \frac{dW^*}{dT} = W^*(1 + \frac{W^*}{0.62198})\left[\frac{4{,}098.03}{(T+237.30)^2}\right] \qquad (5\text{–}55)$$

To compute the $\delta_w{}^*$ in equation 5–52, the value of the greenhouse air temperature from the last previous call to subroutine GH, T_{ai}^{old}, is used in equations 5–53, 5–54, and 5–55. Once $\delta_w{}^*$ is computed, the value of the saturation humidity ratio, $W_v{}^{*old}$, at temperature T_{ai}^{old} is used to compute the intercept, W_0, from equation 5–52.

After W_v, the other variable that requires more explanation is the mass transfer coefficient, K_v (kg/m^2·s). Following Monteith (*1964*, *1973*), it is assumed that the water evaporating in the leaves must pass a leaf stomatal resistance, r_v (m^{2}s/kg), and a series air resistance, r_{ai}. For the soil surface, a similar but admittedly less realistic assumption is used. The soil surface is assumed to have a surface resistance, r_g (parameter 48), which also is in a series with r_{ai}. The overall vegetation resistance, $r_v + r_{ai}$, and the overall soil surface resistance, $r_g + r_{ai}$, are assumed to be parallel, so

$$K_v = \frac{L}{r_{ai} + r_v} + \frac{1}{r_{ai} + r_g} \qquad (5\text{–}56)$$

where L is the leaf area index that the user can imput to the program to change the amount of vegetation in the greenhouse (input 6). Using the leaf area index converts leaf stomatal resistances to crop canopy resistances.

Using the Lewis relation (ASHRAE *1972*, p. 72), the air resistance is computed from the inside air heat transfer coefficient, h_{ai} (W/m^2·°C).

$$r_{ai} = c_a/h_{ai} \qquad (5\text{–}57)$$

where h_{ai} is computed from equation 5–20.

The leaf stomatal resistance, r_v (m^2s/kg), is assumed to be a function of the intensity of solar radiation inside the greenhouse (Kimball *1973*):

$$r_v = b_{11} + b_{12}/(S_o\tau_s + b_{13}) \tag{5–58}$$

where b_{11}, b_{12}, and b_{13} are parameters 45, 46, and 47, respectively.

Solving for T_{ai}, W_{ai}, and T_c

When equations 5–8, 5–9, 5–12, 5–13, 5–14, 5–15, 5–16, 5–24, 5–25, 5–33, 5–34, 5–39, 5–40, 5–44, 5–51, and 5–52, are substituted into equations 5–1, 5–2, and 5–3, rearrangement of the resulting equations yields the following:

$$\begin{aligned}
&T_{ai}(c_a\sum_j M_{xj} + A_cU_i + A_ch_{cl} + h_N + A_wU_w + A_wh_{wl} + A_gk_1)\\
&+ W_{ai}(\lambda\sum_j M_{xj} + A_c\lambda K_{cl} + \lambda K_N + A_w\lambda K_{wl})\\
&+ T_c(-A_cU_i)\\
&= S_i + c_a\sum_j M_{xj}T_{xj} + \lambda\sum_j M_{xj}W_{xj} + A_ch_{cl}T_{ao}\\
&\quad + A_c\lambda K_{cl}W_{ao} + h_NT_{ao} + \lambda K_NW_{ao} + A_wU_wT_{ao}\\
&\quad + A_wh_{wl}T_{ao} + A_w\lambda K_{wi}W_{ao} + A_gk_1T_{g1}
\end{aligned} \tag{5–59}$$

$$\begin{aligned}
&T_{ai}(-\lambda A_gK_v\delta_W{}^*)\\
&+ W_{ai}(\lambda A_gK_v + \lambda\sum_j M_{xj} + A_c\lambda K_{cl} + \lambda K_N + A_w\lambda K_{wl})\\
&+ T_c(0)\\
&= \lambda A_gK_vW_0 + \lambda\sum_j M_{xj}W_{xj} + A_c\lambda K_{ci}W_{ao} + \lambda K_NW_{ao} + A_w\lambda K_{wl}W_{ao}
\end{aligned} \tag{5–60}$$

$$\begin{aligned}
&T_{ai}(-A_cU_i)\\
&+ W_{ai}(0)\\
&+ T_c(2M_cc_c + A_cU_i + A_cU_o)\\
&= S_c + 2M_cc_cT_{xc} + A_cU_oT_{ao}
\end{aligned} \tag{5–61}$$

Equations 5–59, 5–60, and 5–61 form a set of three simultaneous equations with three unknowns, T_{ai}, W_{ai}, and T_c. They are easily solved using Cramer's rule. After T_{ai}, W_{ai}, and T_c are obtained, all of the various fluxes are computed and made outputs from subroutine GH, as listed in appendix E. The values of the derivatives of soil temperature, dT_{gm}/dt, are also computed using equation 5–47 and returned to the main program.

Type 6 Pump or Fan

The type 6 pump or fan is the simplest of all the device models. As illustrated in figure 7, the pump is characterized by specifying the maximum capacity or mass flow rate the pump is capable of delivering as parameter 1. Then, the flow rate out of the pump, output 2, is computed as the product of this maximum capacity and the value of a control variable, input 4. Output 1 is set equal to input 1, and output 3 is set equal to input 3. This permits fluid temperature and humidity ratio information to pass through the pump without modification. For illustration purposes the mass flow rate into the pump can be given in input 2, but the information is not used.

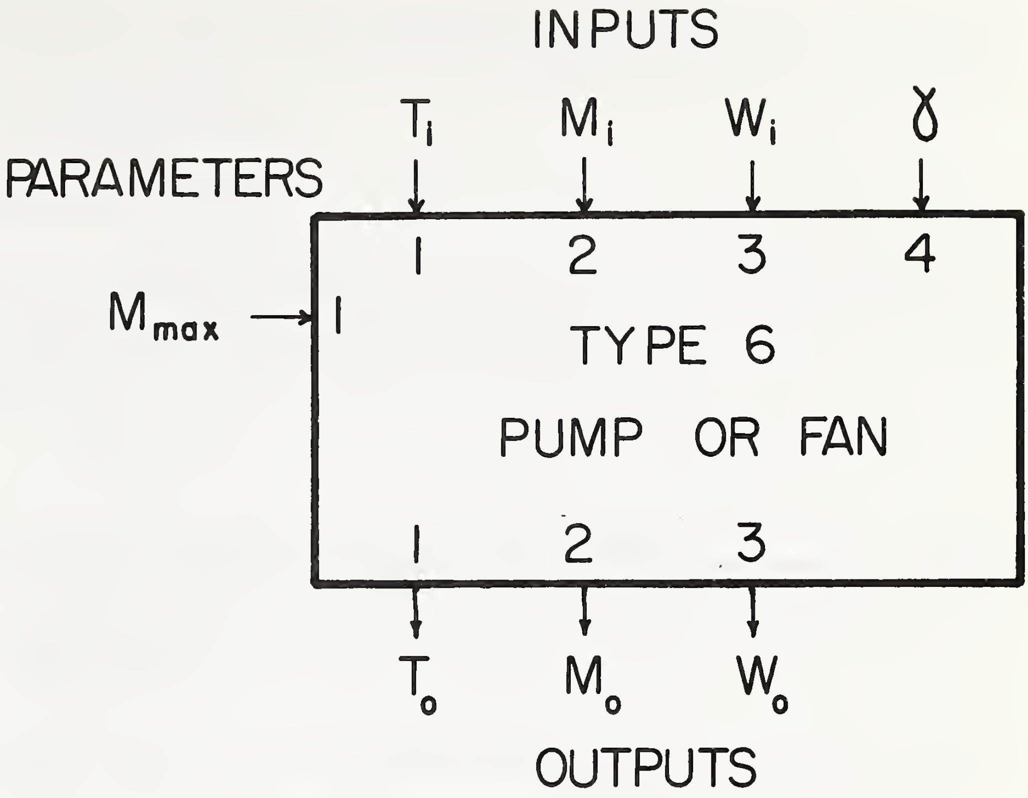

Figure 7.
Functional diagram of a type 6 pump or fan.

Type 7
Tee

Subroutine TEE simulates the action of a tee, two types of mixers, or a flow diverter in an air conditioning duct or fluid pipe. The subroutine handles changes in humidity ratio; but if the entering humidity ratios are set equal to zero, then only sensible heat changes occur and the action of a tee in a liquid flow system is simulated.

The following notations will be used:

- E enthalpy (J/kg)
- T temperature (°C)
- W humidity ratio (kg/kg)
- m mass flow rate (kg/s)
- γ control variable (0 to 1)

Subscripts are as follows:

- $i1$ inlet stream 1
- $i2$ inlet stream 2
- $o1$ outlet stream 1
- $o2$ outlet stream 2

The first (and only) parameter provided by the user specifies the mode: 1, tee; 2, mixer with known inlets; 3, mixer with known outlet, and 4, flow diverter. The action of subroutine TEE for each different mode will now be discussed. See appendix E for the input and output assignments for each mode.

Mode 1, tee

For this mode two streams converge into one. Each of the inlet streams has a definite flow rate (inputs 2 and 5, see appendix E), and the outlet flow rate is the sum of the entering flow rates:

$$m_{o1} = m_{i1} + m_{i2} \tag{7-1}$$

The outlet humidity ratio is the flow weighted average of the inlet humidity ratios (ASHRAE *1972*, p. 104).

$$W_{o1} = \frac{W_{i1}m_{i1} + W_{i2}m_{i2}}{m_{o1}} \tag{7-2}$$

Using equation 7–3, which defines enthalpy (ASHRAE *1972*, p. 100),

$$E = 1{,}005T + W(2.468 \times 10^6 + 1{,}859T) \tag{7-3}$$

Subroutine TEE computes the enthalpies of both entering streams. Then it computes the enthalpy of the outlet stream as the flow weighted average of the inlet enthalpies:

$$E_{o1} = \frac{E_{i1}m_{i1} + E_{i2}m_{i2}}{m_{o1}} \tag{7-4}$$

Finally, the outlet temperature is computed from the outlet enthalpy and humidity ratio using equation 7–5, derived by rearranging equation 7–3:

$$T_{o1} = \frac{E_{o1} - (2.468 \times 10^6)W_{o1}}{1{,}005 + 1{,}859W_{o1}} \tag{7-5}$$

The outlet temperature, flow rate, and humidity ratio are outputs 1, 2, and 3.

Mode 2, mixer with known inlets

For this mode there are two inlet streams, each of which has a maximum flow rate; and the maximums are supplied as inputs 2 and 5. A control variable, input 7, proportions the outlet flow between the two inlet flows:

$$m_{o1} = \gamma m_{i1} + (1 - \gamma)m_{i2} \tag{7-6}$$

When γ equals 1, the outlet flow is inlet stream 1, and when γ equals 0, the outlet flow is inlet stream 2. After the outlet flow has been computed, the outlet humidity ratio (W_{o1}) enthalpy (E_{o1}), and temperature (T_{o1}) are computed just as for mode 1 using equations 7–2 through 7–5.

Mode 3, mixer with known outlet

For this mode there is a pump or fan installed in the single outlet, so the outlet flow rate is known and is supplied to subroutine TEE as input 2. There are two inlets, and their combined flow must equal the given outlet flow. The inlet flows are proportioned between the two streams according to a control variable (input 7). First, the two inlet flow rates are computed from

$$m_{i1} = \gamma m_{o1} \tag{7-7}$$

$$m_{i2} = (1 - \gamma)m_{o1} \tag{7-8}$$

When $\gamma = 1$, the flow is entirely stream 1, and when $\gamma = 0$, it is entirely stream 2. The m_{i1} and m_{i2} are made available as outputs 2 and 5.

Like modes 1 and 2, the inlet temperatures and humidity ratios must be supplied as inputs 1, 3, 4, and 6. After the inlet flows have been computed from equations 7 and 8, the outlet humidity ratio, enthalpy, and temperature are computed using equations 7–2 through 7–5.

Mode 4, flow diverter

For this mode there is one inlet stream of known temperature, flow rate, and humidity ratio, given in inputs 1, 2 and 3. The inlet stream is divided between two outlet streams according to the value of a control variable, γ (input 7). The outlet flow rates, m_{o1} (output 2) and m_{o2} (output 5) are computed from

$$m_{o1} = \gamma m_{i1}$$
$$m_{o2} = (1 - \gamma) m_{i1}$$

When $\gamma = 1$, outlet stream 1 is entirely inlet stream 1 and stream 2 is zero; and when $\gamma = 0$, outlet stream 1 is zero and outlet stream 2 is entirely inlet stream 1. There is no change of temperature or humidity ratio in a flow diverter; so the outlet temperatures (outlets 1 and 4) are merely set equal to input 1, and the outlet humidity ratios (output 3 and 6) are merely set equal to input 3.

It is physically possible for condensation to occur in a tee or mixer (modes 1, 2, or 3) if a hot, nearly saturated air stream is mixed with a cold stream. However such occurrences are to be avoided in practice, and subroutine TEE does not check for supersaturation.

Type 8
Sensible Heat Exchanger

The type 8 sensible heat exchanger is adapted directly from Klein et al. (*1976*). As illustrated in figure 8, the exit temperature of the hot, T_{ho}, and cold, T_{co}, fluids are computed from the entering hot, T_{hi}, and cold, T_{ci}, fluid temperatures and their respective mass flow rates, M_h and M_c.

There are four possible modes of operation: 1, parallel flow; 2, counter flow; 3, crossflow; and 4, constant effectiveness. The value of parameter 1 is used to select the desired mode.

The following notations will be used:

C_c	heat capacity flow rate on cold side (J/s•°C) = $M_c C_{pc}$
C_h	heat capacity flow rate on hot side (J/s•°C) = $M_h C_{ph}$
C_{max}	the larger of C_c or C_h
C_{min}	the smaller of C_c or C_h
C_{pc}	heat capacity of cold side fluid (J/kg•°C)
C_{ph}	heat capacity of hot side fluid (J/kg•°C)
E	heat exchanger effectiveness
M_c	mass flow rate on cold side (kg/s)
M_h	mass flow rate on hot side (kg/s)
Q_t	total heat transfer rate across exchanger (W)
Q_{max}	maximum heat transfer rate across exchanger (W)
R_c	C_{min}/C_{max}
R_u	UA/C_{min}
T_{ci}	cold side inlet temperature (°C)
T_{co}	cold side outlet temperature (°C)

T_{hi} hot side inlet temperature (°C)
T_{ho} hot side outlet temperature (°C)
UA overall heat transfer coefficient (W/°C)
γ control variable

For modes 1, 2, and 3, the effectiveness is computed from the overall heat transfer coefficient.

Mode 1, parallel flow:

$$E = \frac{1 - \exp[-R_u(1 + R_c)]}{1 + R_c} \tag{8–1}$$

Mode 2, counter flow:

$$E = \frac{1 - \exp[-R_u(1 - R_c)]}{1 - (R_c)\exp[-R_u(1 - R_c)]} \tag{8–2}$$

Mode 3, cross flow, hot side unmixed:

$$\text{if } C_{\max} = C_h,\ E = 1 - \exp\left\{ -\frac{1}{R_c}[1 - \exp(-R_u R_c)] \right\}$$

$$\text{if } C_{\min} = C_h,\ E = \frac{1}{R_c}\left\{ 1 - \exp\left[-R_c(1 - \exp(-R_u))\right] \right\} \tag{8–3}$$

For modes 1, 2, and 3,

$$T_{ho} = T_{hi} - E(C_{\min}/C_h)\,(T_{hi} - T_{ci}) \tag{8–4}$$

$$T_{co} = T_{ci} + E(C_{\min}/C_c)\,(T_{hi} - T_{ci}) \tag{8–5}$$

$$Q_T = EC_{\min}(T_{hi} - T_{ci}) \tag{8–6}$$

For mode 4, constant effectiveness supplied by user,

$$\begin{aligned} &\text{if } C_{\min} = C_h,\ Q_{\max} = C_h(T_{hi} - T_{ci}) \\ &\text{if } C_{\min} = C_c,\ Q_{\max} = C_c(T_{hi} - T_{ci}) \end{aligned} \tag{8–7}$$

$$Q_T = EQ_{\max} \tag{8–8}$$

$$T_{ho} = T_{hi} - Q_T/C_h \tag{8–9}$$

$$T_{co} = T_{ci} + Q_T/C_c \tag{8–10}$$

There are two special cases. For mode 2, if

$$|R_c - 1| < 0.01, \text{ then } E = R_u/(R_u + 1)$$

For modes 1, 2, and 3, if $R_u \leq 0.01$, then

$$E = 1 - \exp(-R_u)$$

The sequence number codes for the parameters, inputs, and outputs are given in figure 8 and appendix E. All except input 5 are explained by the preceding equations. Input 5 is the control variable that is used by other routines to control the rates of flow of the two fluids. If it is generated by a type 4 thermostat, the flows are reduced by a proportion of their maximums, the proportion corresponding to the fraction of a simulation time increment that the heat exchanger is actually in operation. In other words, a type 4 thermostat converts cyclic on-off flow to an average steady flow. Because the performance of a heat exchanger depends on actual flow rates, the control variable must be supplied to subroutine SXR (as input 5) to scale the flow rates up to actual and then to scale output temperatures and energy exchange down to average. If the exchanger is to be operated continuously, input 5 can be set equal to 1.0.

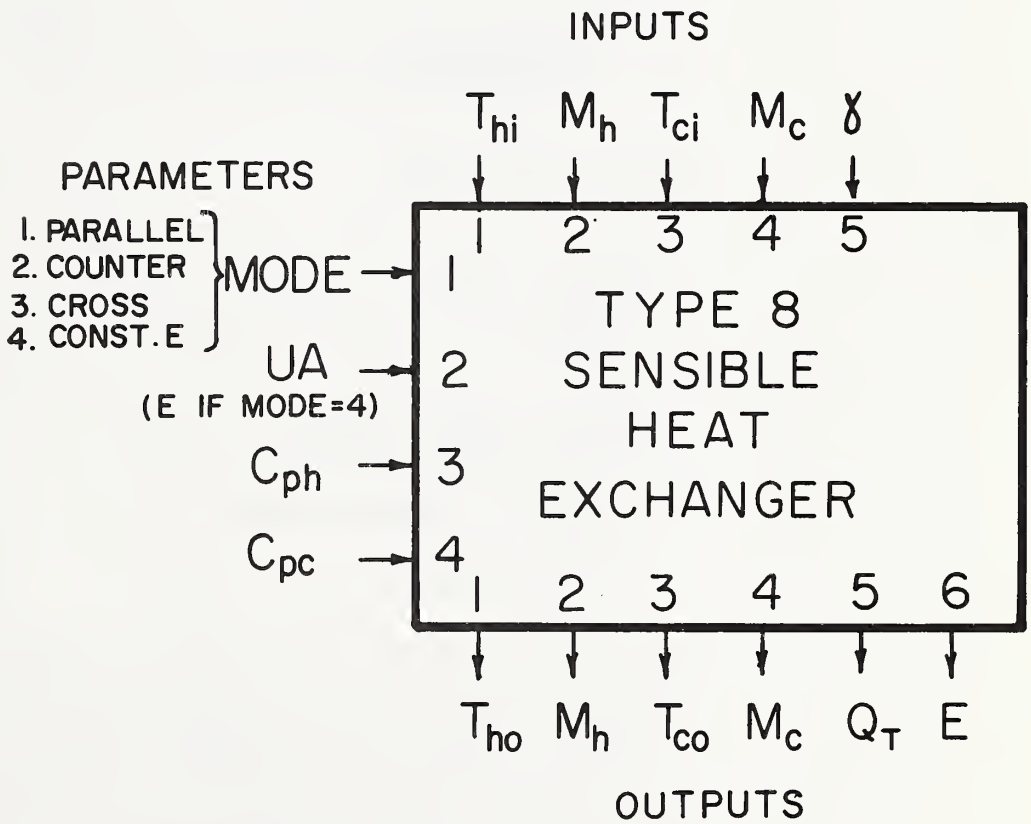

Figure 8.
Functional diagram of a type 8 sensible heat exchanger.

Type 9
Latent and Sensible Heat Exchanger

The type 9 latent and sensible heat exchanger can be used to model wet devices, such as cooling towers, air washers, and dehumidifying coils, as well as dry devices, such as the heating coils modeled by the type 8 sensible heat exchanger. Dehumidifying coils which might be dry, partially wet, or completely wet can also be handled. The type 9 exchanger has two modes of operation. Mode 1 is for direct-contact devices, such as cooling towers or air washers. Mode 2 is for noncontact devices, such as heating or cooling coils which have a wall of metal or other material to separate the liquid from the air.

The following symbols will be used:

A_{cs} cross sectional face area (m^2)
a_H heat transfer area per cubic meter (m^2/m^3)
a_M mass transfer area per cubic meter (m^2/m^3)
c specific heat (J/kg•°C)
E enthalpy (J/kg)
G mass flow rate (kg/s•m^2 of cross-sectional face area)
h heat transfer coefficient (W/°C•m^2 of heat exchange area)
K_D mass transfer coefficient (kg/s•m^2 of mass exchange area)
ℓ length (m)
R resistance to heat flow (m^2°C/W)
T temperature (°C)
U combined heat transfer coefficient for liquid film and metal (W/m^2•°C)
W humidity ratio (kg/kg)
γ control variable

Subscripts are as follows:

a air
am moist air
H refers to heat transfer area
i interface
L liquid
m metal or material
M refers to mass transfer area
v vaporization
vo vaporization at base temperature
1 entering
2 exiting

Analogous to the type 8 exchanger, the type 9 exchanger computes the exit air temperature (T_{a2}), humidity ratio (W_{a2}), and liquid temperature (T_{L2}) from entering air temperature (T_{a1}), humidity ratio (W_{a1}), and liquid temperature (T_{L1}). The basic model of the mechanisms of heat and mass exchange at the microscopic level follows ASHRAE (*1972*) and is illustrated in figure 9. Energy is transferred by convection through film resistances from (or to) the bulk air at T_a, W_a, E_a to (or from) the bulk liquid at T_L. For direct-contact devices (mode 1), the humidity ratio at the interface, W_i, is the saturation humidity ratio at interface temperature, T_i. For noncontact devices (mode 2), a wall with resistance R_m separates the liquid from the air. Then, if W_a is less than the saturation humidity ratio at T_i, the interface is assumed to be dry, with $W_i = W_a$. This special dry case is the same as that of a type 8 sensible heat exchanger. However, when the saturation humidity ratio at T_i is less than W_a, conden-

sation is assumed to occur at the interface, as in a dehumidifier. The resistance of the condensate is neglected in this model, however.

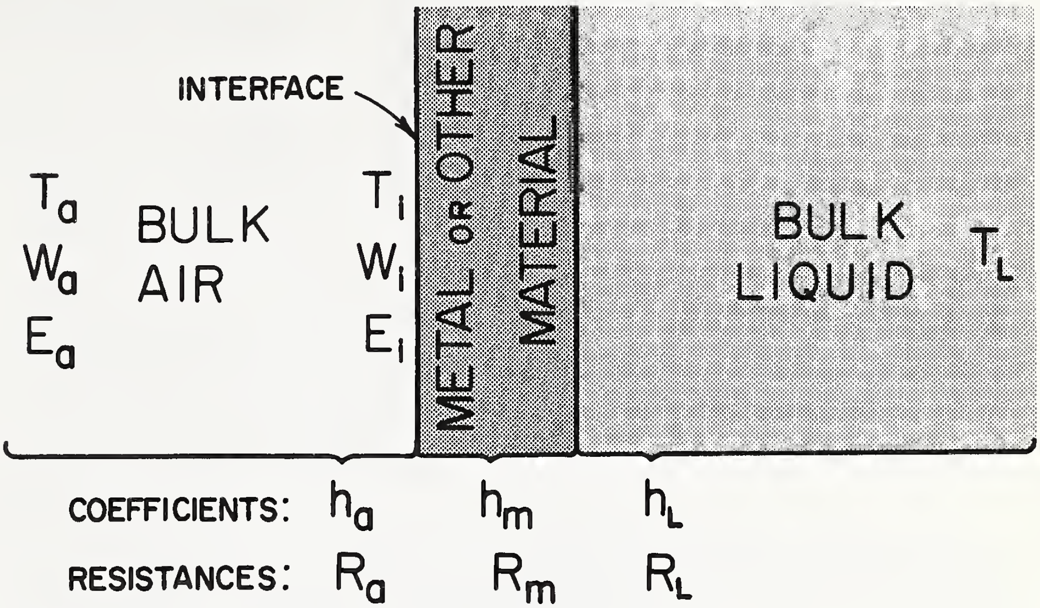

Figure 9.
Illustration of the microscopic films that impede the transfer of heat and mass between bulk air and bulk liquid in a type 9 latent and sensible heat exchanger.

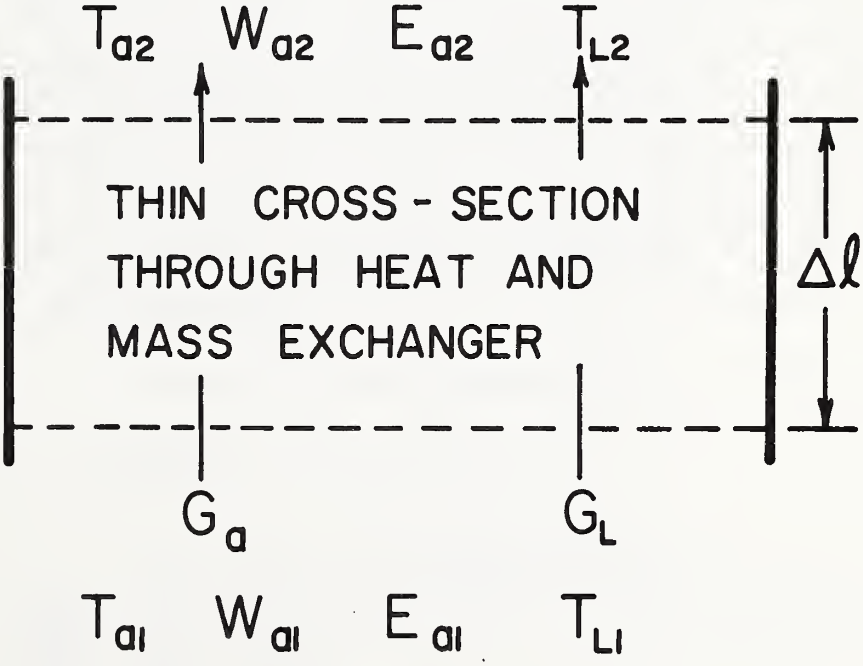

Figure 10.
Illustration of the macroscopic exchange of heat and mass between an air stream and a liquid stream flowing parallel (or counter) through a thin cross section of a type 9 latent and sensible heat exchanger.

The macroscopic picture of the heat and mass transfer is illustrated in figure 10. Liquid at mass flow rate G_L (kg/m²•s) and air at mass flow rate G_a (kg/m²•s) are flowing through a cross section of area, A_{cs}, and thickness, $\Delta\ell$, of the heat exchanger. The flow can be either parallel or counter but, for the immediate purposes of illustration, will be taken as parallel.

Following ASHRAE (*1972*), the equation for heat transfer from the interface to the air is written

$$G_a c_{am} dT_a = h_a a_H (T_i - T_a) d\ell \tag{9–1}$$

where

$$c_{am} = 1{,}005 + 1{,}859 W_a \tag{9–2}$$

The equation for mass transfer is

$$-dG_L = G_a dW = K_D a_M (W_i - W_a) \tag{9–3}$$

For mode 2 if $T_i > T_a$, then $W_i = W_a$ and $dG_L = dW = 0$. Combining equations 9–1 and 9–3 with the enthalpy of vaporization, E_v, yields

$$G_a (c_{am} dT_a + E_{vo} dW) = [K_D a_M (W_i - W) E_v + h_a a_H (T_i - T_a)] d\ell \tag{9–4}$$

Assuming that the material in the chamber wets completely so that $a_H = a_M$, and utilizing the Lewis relation for an air-water system which states $h_a = K_D c_{am}$, equation 9–4 reduces to

$$G_a dE_a = K_D a_M (E_i - E_a) d\ell \tag{9–5}$$

In deriving equation 9–5, it is also assumed that the percentage change of G_L due to evaporation of water is small. Since there must be an energy balance,

$$G_a dE_a = G_L c_L dt_L \tag{9–6}$$

The equation for heat transfer from water to the interface is

$$G_L c_L dT_L = U (T_L - T_i) d\ell \tag{9–7}$$

where, in reference to figure 9, U is given by

$$U = \frac{1}{R_L + R_m} \tag{9–8}$$

Combining equations 9–5, 9–6, and 9–7 yields

$$\frac{E_i - E_a}{T_L - T_i} = -\frac{U}{K_D a_M} = -\frac{U c_{am}}{h_a a_H} \tag{9–9}$$

Also from equation 9–5,

$$\ell = \frac{G_a}{K_D a_M} \int \frac{dE}{E_i - E_a} \tag{9–10}$$

Equation 9–6 describes how the air enthalpy changes with water temperature, and equation 9–7 shows how the interface temperature changes to accommodate this change in air and water conditions. Starting with a known inlet air condition at the bottom (top for parallel flow) and a known bottom (exit) water temperature and a known entrance water temperature, and considering the air to move through the tower in a series of steps, the interface associated with each of these steps can be calculated and finally also the exit conditions for the air. Then, equation 9–10 yields the length of the exchanger. This procedure was developed by Mickley (*1949*) and is described in the ASHRAE (*1972*). It is programmed as a routine within the type 9 heat exchanger.

The Mickley routine computes exit air conditions and length of column from entering air and liquid conditions and exiting liquid conditions. To compute the liquid exit conditions instead, the type 9 heat exchanger first guesses an exit liquid temperature and then uses the Mickley routine to calculate the length of the exchanger. Newton iteration is used to improve the guess of the exit liquid temperature until the computed length equals the actual length.

The rates of heat and mass transfer are controlled by the transfer coefficients, $h_L a_H$ and $K_D a_M$. These transfer coefficients are computed from equations containing user-supplied coefficients. Referring to appendix E, parameters 6, 7, and 8 are the coefficients C_1, C_2, and C_3, respectively, for computing $K_D a_M$ as follows:

$$K_D a_M = C_1 G_a^{C_2} G_L^{C_3} \tag{9–11}$$

The K_D is the mass transfer coefficient with respect to the area available for mass transfer within the exchanger (kg/s•m_2 of mass exchange area), and a_M is the mass transfer area per volume of exchanger. Generally, for cooling towers and other devices filled with irregular material or irregular water drops, only the product $K_D a_M$ can be determined. The correlation coefficients in equation 9–11 have been determined for aspen excelsior pads (Kimball et al. *1977*) and some other materials (Furlong *1975*). Data also exist in the literature which correlate the mass transfer coefficient, K_D, by itself against Reynolds number (air velocity) for many simple geometries, or it can be calculated from the heat transfer coefficient ($K_D \approx h/c_{am}$) for which an even larger body of data has been published (ASHRAE *1972*). For these simple geometries, such as in cooling or heating coils, the mass transfer area per unit volume, a_M, can often be calculated from physical measurements. Then, if the correlation for K_D is of the form

$$K_D = C_1' G_a^{C_2} G_L^{C_3} \tag{9–12}$$

the C_1 for equation 9–11 can be obtained from

$$C_1 = C_1' a_M \tag{9–13}$$

If there is no dependence on liquid flow rate, as in noncontact exchangers, C_3 (parameter 8) should be set equal to zero.

Similar to the case for $K_D a_M$, parameters 9, 10, and 11 are the coefficients C_4, C_5, and C_6, respectively, for computing $h_L a_H$ as follows:

$$h_L a_H = C_4 G_a^{C_5} G_L^{C_6} \tag{9–14}$$

These coefficients are analogous to those in equation 9–11, and all the same comments apply. In addition, however, for finned coils the user must remember to account for the smaller internal area exposed to the liquid as compared to the external area exposed to the air. This can be done by using a C_4 that is reduced by a factor equal to the ratio of internal to external surface area (ASHRAE *1975*, p. 6.10; Air Conditioning and Refrigeration Institute *1972*).

Parameter 12 (appendix E) is the metal or structure resistance of a noncontact heat exchanger R_m ($m^3 \cdot °C/W$). If the exchanger is normally wet, a condensate resistance should be added to R_m; otherwise the condensate resistance is zero. For mode 1, R_m should be set equal to zero. The combined liquid-metal heat transfer coefficient, U, is computed from $U = 1/(R_m + (1/h_L a_H))$.

The control variable (input 8) is the one used by other routines to control the rates of flow of the fluid and the air. If it is generated by a type 4 thermostat, the flows are reduced from their maximums by a proportion corresponding to the fraction of a simulation time increment that the heat exchanger is actually in operation. In other words, a type 4 thermostat converts cyclic on-off flow to an average steady flow. Like the type 8 sensible heat exchanger, the performace of a type 9 latent and sensible heat exchanger depends on actual flow rates. Therefore, the control variable must be supplied to subroutine LXR (as input 8) to scale the flow rates up to actual and then to scale output temperatures, humidity ratios, and energy and water exchanges down to average. If the exchanger is operated continuously, input 8 can be set equal to 1.0.

The other parameters, inputs, and outputs are self-explanatory as defined in appendix E.

Type 10 Flat-Plate Solar Collector

The type 10 flat-plate solar collector is adapted directly from Klein et al. (*1976*) and uses the model (HWB) of Hottel and Woertz (*1942*), Whillier (*1967*), and Bliss (*1959*) because of its computational simplicity and its excellent agreement with more elaborate models.

The following symbols will be used:

A collector area (m^2)
C_p fluid thermal capacitance ($J/kg \cdot °C$)
F' collector-geometry efficiency factor (dimensionless)
F_R collector efficiency factor defined in equation 10–2
H_B rate of beam radiation per unit area incident upon the tilted collector surface (W/m^2)
H_D rate of diffuse radiation per unit area incident upon the tilted collector surface (W/m^2)
H_T rate of total radiation per unit area incident upon the tilted collector surface (W/m^2)
h_w heat transfer coefficient off top glass cover ($W/m^2 \cdot °C$)
KL product of the extinction coefficient and the thickness of each glass cover (dimensionless)
$\dot{m}$ collector fluid flow rate (kg/s)
N number of glass covers (1, 2, or 3)
Q_u rate of energy collection (W)

s collector tilt from horizontal (degrees)
T_A absolute ambient temperature (K)
T_a ambient temperature (°C)
T_i inlet fluid temperature (°C)
T_o outlet fluid temperature (°C)
T_p mean absolute collector plate temperature (K)
U_{be} loss coefficient per unit collector area accounting for bottom and edge losses ($W/m^2 \cdot °C$)
U_L collector overall energy loss coefficient per unit collecter area ($W/m^2 \cdot °C$)
W windspeed (m/s)
α collector plate absorptance for solar radiation
ϵ_g emittance of glass covers
ϵ_p emittance of plate
γ control variable to scale average flow rate to actual
η_g refractive index of the glass (assumed to be 1.526)
θ_T incidence angle of beam radiation on the collector surface (degrees)
τ transmittance of the N cover(s)

The HWB model expresses the rate of energy collection, Q_u, as

$$Q_u = AF_R[H_T\tau\alpha - U_L(T_i - T_a)] \tag{10-1}$$

where

$$F_R = \frac{\dot{m}C_p}{AU_L}\left[1 - \exp\left(-\frac{F'U_LA}{\dot{m}C_p}\right)\right] \tag{10-2}$$

The geometry efficiency factor F', a function of the collector construction, can be determined in the manner given by Bliss (*1959*) or Duffie and Beckman (*1974*). The overall energy loss coefficient, U_L, is a complicated function of the collector construction and (to a lesser extent) its operating conditions. If the dependence of U_L upon operating conditions is ignored, U_L is a constant for a specified collector; its value can be determined (at the estimated average operating conditions) from the information given in chapter 7 of Duffie and Beckman (*1974*). Alternatively, the following expression, developed by Klein (*1975*), can be used to approximate the value of U_L:

$$U_L = \frac{1}{\dfrac{N}{\dfrac{C}{T_p}\left[\dfrac{(T_p - T_A)}{N+f}\right]^{0.33}} + \dfrac{1}{h_w}} + \frac{\sigma(T_p^2 + T_A^2)(T_p + T_A)}{\dfrac{1}{\epsilon_p + 0.05N(1 - \epsilon_p)} + \dfrac{2N + f - 1}{\epsilon_g} - N} + U_{be} \tag{10-3}$$

where
$$h_w = 5.7 + 3.8W \tag{10-4}$$
$$f = (1 - 0.04h_w + 0.005h_w^2)(1 - 0.091N) \tag{10-5}$$
$$C = 365.9(1 - 0.00883s + 0.0001298s^2) \tag{10-6}$$

The transmittance of an N-glass cover system, τ, is in general a function of the angle at which beam and diffuse radiation strike the cover surface. If the incidence angle of diffuse radiation is assumed to be an average of 60° (as suggested by Hottel and Woertz *1942*), τ can be calculated from

$$\tau = (H_B/H_T)\{\tau'_{\theta_T}\exp[-KL/\cos(\theta_1)]\} + (H_D/H_T)\{\tau'_{60°}\exp[-KL/\cos(\theta_2)]\} \quad (10\text{–}7)$$

where τ'_x = the transmittance of an N-glass cover system for radiation incident on the cover surface at an angle, x, accounting for reflection only and neglecting the absorptance of radiation by the glass. The value for τ'_x is given in figure 6.1.3 of Duffie and Beckman (*1974*).

$\theta_1 = \arcsin[\sin(\theta_T)/\eta_g]$

$\theta_2 = \arcsin[\sin(60°)/\eta_g]$

As seen in figure 6.2.1 of Duffie and Beckman, τ is essentially constant for incidence angles between 0° and 40°. As a result, the angular dependence of τ may be unimportant for some collector orientations.

After Q_u has been computed, the outlet fluid temperature is computed from

$$T_o = T_i + Q_u/(\dot{m}C_p) \quad (10\text{–}8)$$

Equations 10–1 and 10–8 apply only when fluid is being pumped through the collector. When $\dot{m} = 0$, as will normally be the case at night, Q_u is set equal to zero, and the outlet fluid temperature is computed from

$$T_o = \frac{H_T\tau\alpha}{U_L} + T_a$$

The type 10 solar collector has four modes which have different paramter and input requirements and different degrees of computational difficulty; however, the first five parameters and the first four inputs are the same for all four modes (appendix E).

For mode 1 the user supplies the value of the transmittance, τ, as parameter 6 and the loss coefficient, U_L, as parameter 7. This saves considerable computation time but may introduce significant errors for some cases. Values for parameters 8 through 12 are unneeded and can simply be set equal to zero. Similarly, inputs 5 through 7 are unused and can be connected to any output.

For mode 2, U_L is computed from equation 10–3, so additional parameters and input must be specified as follows: Parameters 8, number of panes (N); parameter 11, tilt from horizontal (s); and input 6, windspeed (W). Now, unused parameters 7 and 12 may be set equal to zero, and unused inputs 5 and 7 may be connected to any output.

For mode 3, τ is computed from equation 10–8, but the user specifies a constant value U_L in parameter 7. Referring again to appendix E, the user must also now specify parameter 8, number of panes (N); parameter 12, extinction coefficient thickness product (KL); input 5, diffuse solar radiation (H_D); and input 7, angle of incidence of beam radiation onto the collector surface (θ_T). Parameters 6, 9, 10, and 11 are unused and can be set equal to zero. Input 6 is also unused and can be connected to any output.

For mode 4, both τ and U_L are variables computed by the program. This mode requires the most computational effort but should also be the most accurate, provided, of course, that the parameters and inputs are accurate. As shown in appendix E, all inputs are used in mode 4, and only parameters 6 and 7 are unused and can be set equal to zero.

Like the type 8 and 9 heat exchangers, the type 10 solar collector is another device whose performance depends on actual flow rate. Because the mass flow rate supplied as input 2 might be an average flow rate from a pump for a time increment, subroutine CLECR also requires that the pump's control variable, γ, be input 8. This control variable is used to scale up the flow rate to the actual for the portion of the time that the collector is in operation and then to scale down the energy collection and output temperature to average for the time increment. For continuous operation, γ can be set equal to 1.0

Type 11 Stratified-Fluid Tank with Internal Heater

The type 11 stratified-fluid tank with internal heater is also adapted directly from Klein et al. (*1976*). The thermal performance of such a sensible-energy storage tank, subject to thermal stratification, is modeled by assuming that the tank consists of N fully mixed equal-volume segments, as shown in figure 11. The degree of stratification is determined by the value of N. If N is equal to 1, the storage tank is modeled as a fully mixed tank and no stratification effects are possible. Several investigators (Close *1967*, Gutierrez et al. *1974*) have suggested that a tank model consisting of three segments ($N=3$) provides the best compromise between accuracy and computational effort when an estimation of stratification effects is needed.

The following notations will be used:

A_i	surface area of the ith tank segment (m^2)
C_{pf}	specific heat of the tank fluid (J/kg•°C)
H	tank height (m)
i	tank segment number, with $i=1$ for the top (hottest) segment
ℓ	number of the tank segment in which the heating element is located $1 \leq \ell \leq N$
ℓ_T	number of the tank segment in which the thermostat of the heating element is located $1 \leq \ell_T \leq N$
M_i	mass of fluid in the ith section (kg)
M_L	fluid mass flow rate to the load and/or of the makeup fluid (kg/s)
M_h	fluid mass flow rate to and from the heat source (kg/s)
$\dot{m}$	fluid mass flow rate inside the tank (kg/s)
N	number of equal-volume, fully mixed (uniform temperature) tank segments
$\dot{Q}_{env}$	rate of energy loss from the tank to the surroundings (W)
$\dot{Q}_{HE}$	maximum rate of energy input by the heating element (W)
$\dot{Q}_l$	rate of energy input by the heating element (W)
$\dot{Q}_{tank}$	rate at which sensible energy is removed from the tank to supply the load (W)
S_h	number of the tank segment to which the fluid from the heat source is closest in temperature $1 \leq S_h \leq N$
S_L	number of the tank segment to which the fluid replacing that extracted to supply the load is closest in temperature $1 \leq S_L \leq N$
t	time (s)
T_{env}	temperature of the environment surrounding the tank (°C)
T_i	temperature of the ith tank segment (°C)
T_h	temperature of the fluid entering the storage tank from the heat source (°C)

T_L temperature of the fluid replacing that extracted to supply the load (°C)
T_ℓ temperature of tank segment having the internal thermostat (°C)
T_N temperature from bottom of tank (°C)
T_o initial average tank temperature (°C)
T_{set} set temperature of the heating element thermostat (°C)
U loss coefficient between the tank and its environment (W/m²•°C)
V tank volume (m³)
ΔE internal energy change of the tank (J)
α_i a control function defined by

$$\alpha_i = \begin{cases} 1 \text{ if } i = S_h \\ 0 \text{ otherwise} \end{cases}$$

β_i a control function defined by

$$\beta_i = \begin{cases} 1 \text{ if } i = S_L \\ 0 \text{ otherwise} \end{cases}$$

γ_{HE} external control variable. Vary from 0 to 1 to vary heater output from 0 to $\dot{Q}_{HE}$. If $\eta = 0$, this input is unused and can be connected to any output.
γ_{TS} internal thermostat variable

$$\gamma_{TS} = \begin{cases} 0 \quad \text{if } T_\ell \geq T_{set} + 1 \\ 1 \quad \text{if } T_\ell \leq T_{set} - 1 \\ [1 + \sin(\pi(T_\ell - T_{set} - 2)/2)]/2 \text{ if } T_{set} - 1 < T_\ell < T_{set} + 1 \end{cases}$$

γ_i a control function defined by

$$\gamma_i = M_h c_{pf} \sum_{j=1}^{i-1} \alpha_j - M_L c_{pf} \sum_{j=i+1}^{N} \beta_j$$

δ_i a control function defined by

$$\delta_i = \begin{cases} 1/\ell & \text{if } i \leq \ell \\ 0 & \text{otherwise} \end{cases}$$

η flag to indicate whether external control variable will be used (1) or not (0).
ρ_f fluid density (kg/m³)

The model includes an optional electric resistance heating element which is controlled by an internal thermostat or which, as an additional option, is controlled by the internal thermostat plus an external control variable. One modification from the TRNSYS model of Klein et al. (*1976*) is that the internal thermostat is not simply an on-off device. TRNSYS "sticks" the thermostat in one state or the other when on-off oscillations occur with successive iterations (see description of type 4 thermostat). In this type 11 tank, the internal thermostat has a 2°C dead band centered on the set-point temperature. When the tank temperature is within the dead band, the program performs a sine interpolation to produce an output from the heating element that changes smoothly rather than abruptly from on to off. This modification will produce a

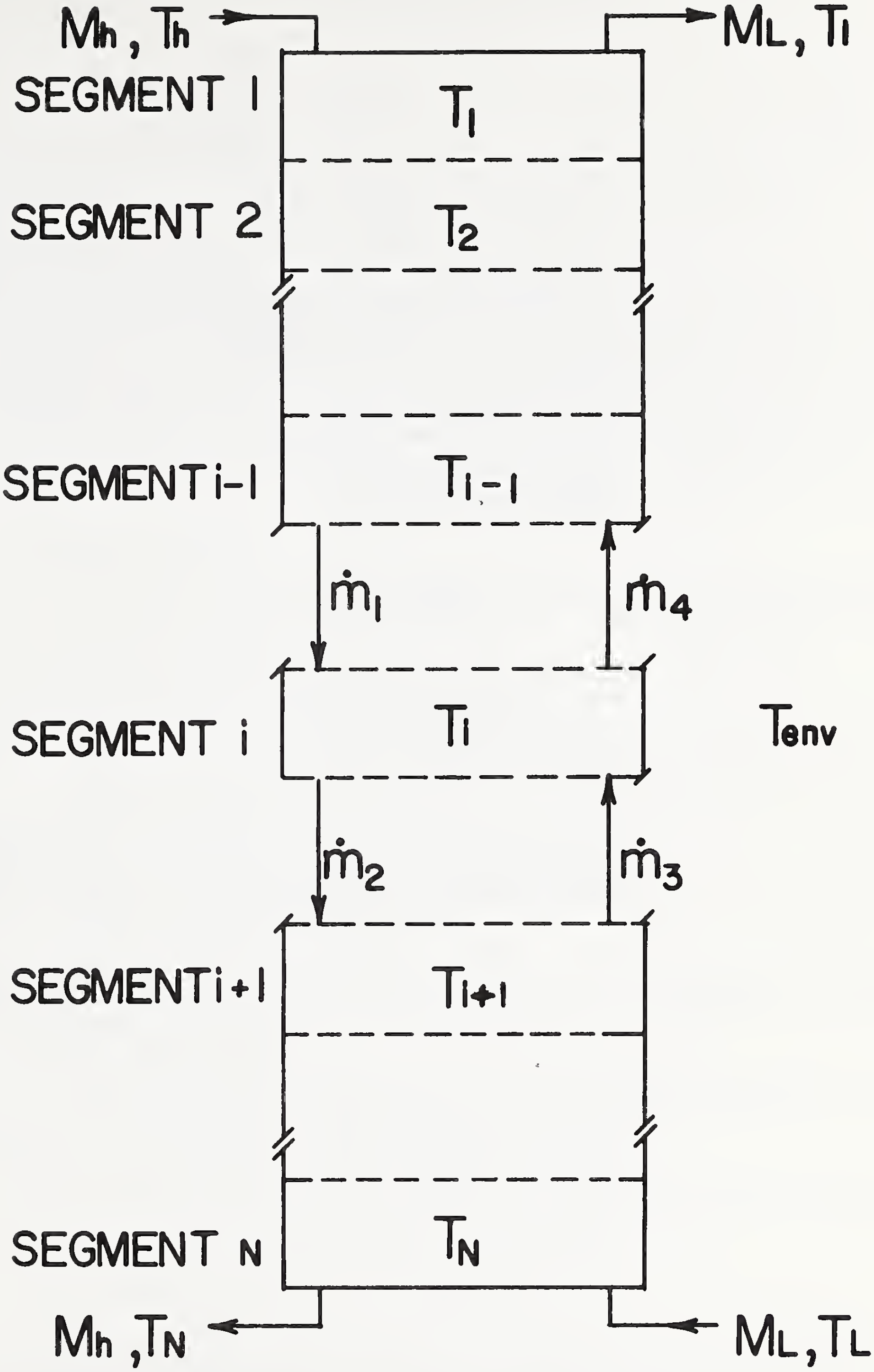

Figure 11.
Schematic diagram of the segments in a type 11 stratified-fluid tank.

more stable simulation for most cases. For tank models in which $N>1$, the position (tank segment number) of the heating element and the thermostat must be specified. The model assumes that the energy supplied to the tank from the heating element is evenly distributed to all tank segments above and including the heating element.

The rate of energy delivery to the tank from the heating element is

$$\dot{Q}_l = \begin{cases} \dot{Q}_{HE}\,\gamma_{TS}\,\gamma_{HE} & \text{if } \eta = 1 \\ \dot{Q}_{HE}\,\gamma_{TS} & \text{if } \eta = 0 \end{cases}$$

An assumption employed in this model when $N > 1$ is slightly different from that used in the algorithm described by Close (*1967*) and Gutierrez et al. (*1974*). They assumed that there is no internal mixing of the fluid streams flowing up from the bottom of the tank and down from the top before they enter each segment. In reference to figure 11, their assumption implies that $\dot{m}_1 = \dot{m}_2$ and $\dot{m}_3 = \dot{m}_4$ and that $\dot{m}_1$ and $\dot{m}_2$ are unaffected by $\dot{m}_3$ and $\dot{m}_4$. The alternative assumption—that the fluid streams flowing up and down are fully mixed before they enter each segment—is used in the type 11 model. This assumption implies that $\dot{m}_1$ is added to $\dot{m}_4$ and that $\dot{m}_2$ is added to $\dot{m}_3$ to yield a resultant flow, either up or down. An energy balance on the *i*th segment (neglecting losses) is then

$$M_i C_{pf} \frac{dT_i}{dt} = \begin{cases} (\dot{m}_1 - \dot{m}_3)\, C_{pf}\, (T_{i-1} - T_i) & \dot{m}_1 \geq \dot{m}_3 \\ (\dot{m}_3 - \dot{m}_1)\, C_{pf}\, (T_{i+1} - T_i) & \dot{m}_1 < \dot{m}_3 \end{cases}$$

It has been found that this latter assumption generally permits a higher degree of stratification than the former and yields results which agree well with experimental measurements (Klein et al. *1976*).

The model assumes that the energy input to the tank from the heating element is evenly distributed to all tank sections above and including the heating element. Then, a detailed energy balance written about the *i*th tank segment is expressed as

$$\begin{aligned} M_i C_{pf} \frac{dT_i}{dt} = {} & \alpha_i M_h C_{pf}(T_h - T_i) + \beta_i M_L C_{pf}(T_L - T_i) + UA_i\,(T_{\text{env}} - T_i) \\ & + \begin{cases} \gamma_i (T_{i-1} - T_i) & \text{if } \gamma_i > 0 \\ \gamma_{i+1}(T_i - T_{i+1}) & \text{if } \gamma_{i+1} < 0 \end{cases} \\ & + \quad \delta_i \dot{Q}_i \qquad \text{for } i = 1, N \end{aligned}$$

The temperatures of each of the tank segments are determined by the numerical integration of the time derivatives expressed in the above equation.

A rate of energy loss to the environment is computed from

$$\dot{Q}_{\text{env}} = \sum_{i=1}^{N} UA_i\,(T_i - T_{\text{env}})$$

The rate at which energy is removed from the tank to supply the load is computed from

$$\dot{Q}_{\text{tank}} = M_h C_{pf} (T_i - T_L)$$

The change in stored heat since initial time is computed from

$$\Delta E = C_{pf}\, \rho_f\, V \sum_{i=1}^{N} (T_i - T_o)$$

The sequence codes for the parameters, inputs, outputs, and derivatives are listed in appendix E. All have already been discussed except for the initial values of the dependent variables that must be both integrated and estimated by the user. In this case, these are the initial temperatures of the tank segments. The closer these initial estimates are to the final computed temperatures, the fewer iterations will be required. However, the final temperatures are dependent on the estimated initial temperatures. When daily cycles of data are available, the user should repeat the first day's data a few times to reduce the dependence on the initial estimates.

Type 12 Time-Dependent Forcing Function

The time dependent forcing function (TIMFN) is also adapted from Klein et al. (*1976*). It can model a timer that produces a discrete signal to turn a device on or off at a set time of day, or it can model seasons of the year that produce a gradually changing deep soil temperature. Its purpose is to produce a variable, F, that is a repetitive or nonrepetitive function of time. The pattern of this function is established by a set of discrete data points indicating its values at various times through one cycle. Linear interpolation is used to produce a continuous output from the discrete data.

The following symbols will be used:

- C_T the cycle time (h). It is the time span after which the pattern repeats itself. It can be the total simulation time.
- N one less than the number of data pairs used to define the function
- t elapsed time since start of simulation (h)
- F function value at time t
- t_o time of first given point (equals elapsed time to start of repetitive cycle after start of simulation) (h)
- F_o given function value at t_o
- t_1 time of second given point (h)
- F_1 given function value at t_1
- t_2 time of third given point (h)
- F_2 given function value at t_2
- t_N time of last given point (equals elapsed time to end of repetitive cycle after start of simulation) (h)
- F_N given function value at t_N
- t_R time derived from the simulation time, t, by repetitively subtracting or adding whole numbers of time cycles, C_T so that $t_o \le t_R \le t_N$

The first computations performed by TIMFN are to compute the relative time t_R, so that

$$t_o \le t_R \le t_N$$

Then TIMFN searches for the individual given points (t_i, F_i and t_{i+1}, F_{i+1}) that are closest to t_R on each side and computes the desired function value using a linear interpolation:

$$F = F_i + (F_{i+1} - F_i)(t_R - t_i)/(t_{i+1} - t_i)$$

F is output 1 from TIMFN. Output 2 is $(1 - F)$, which can be used for negative logic.

Two successive given points can have the same time value to define a step change. In this case, the function value of the first point given in the parameter sequence will

be used for interpolating if $t_R \leq$ the time at the step and vice versa. For a repetitive cycle, the function value for the first point, F_o, must equal the value of the last point, F_N, to avoid a step change.

Type 13 Infinite-Volume Storage Reservoir

The type 13 infinite-volume storage reservoir models a source of water (or whatever) so large that it is unchanging for the length of a simulation run. The user supplies values to RSVOR as parameters, and when called, RSVOR simply passes them on as outputs. As listed in appendix E, the first parameter is N , the total number of parameters. Then the rest of the parameters are the constant values of entities that are normally variable inputs to other MEB subroutines. The outputs from RSVOR are set equal to these parameters.

OUTPUT (1) = PARAMETER (2)
OUTPUT (2) = PARAMETER (3)
OUTPUT (i) = PARAMETER (i + 1)

In addition to modeling a reservoir, RSVOR provides a useful aid for debugging new MEB subroutines. Constant known values (often for a special case) can be given as parameters to RSVOR, and the inputs of the new routine connected to the outputs of RSVOR.

Type 14 Complicated Greenhouse

The type 14 complicated greenhouse is illustrated in figure 12. Each arrow represents a flux of energy, with the direction of arrows taken as positive. The fluxes are all computed individually and are of solar radiation, S; thermal radiation, R; convection, C; conduction, G; infiltration, I; natural ventilation, N; and energy from external devices, X. Energy balances are written for several surfaces and the air in the greenhouse, as was done by Businger (*1963*), Selcuk (*1970*), Takakura et al. (*1971*), Iwakiri (*1971*), Kimball (*1973*), Maher and O'Flaherty (*1973*), Olszewski and Trezek (*1976*), Takami and Uchijima (*1977*), Froehlich et al. (*1979*), Kindelan (*1980*), Van Bavel et al. (*1981*), Chandra et al. (*1981*), Avissar and Mahrer (*1982*), and Glaub and Trezek (*1981*). The transfer coefficients are all computed individually without using any overall U factors. Energy balances are written for the outer cover surface, inner cover, vegetation, soil surface, curtain heat exchanger, inside air, and a soil energy storage layer. A moisture balance also is written for the inside air. These energy and moisture balance equations are solved for the outer cover temperature, T_{co}; inner cover temperature, T_{ci}; vegetation temperature, T_v; soil surface temperature, T_g; curtain heat exchanger temperature, T_e; inside air temperature, T_{ai}; inside air humidity ratio, T_{ai}, and soil storage layer temperature T_{gs}.

The type 14 complicated greenhouse model can simulate almost any type of conventional greenhouse as well as most proposed solar greenhouses. The optical and thermal properties of the cover can be varied under the control of other devices, such as type 12 time clocks, to simulate pulling a thermal screen at night or shade cloth in the summertime. Provision is also made for collecting energy from a fluid roof (Damagnez *1976,* Van Bavel et al. *1981*) and for storing energy below the greenhouse in the soil (Dale et al. *1979*) or porous concrete (Mears et al. *1977*). Curtain heat exchangers (Simpkins et al. *1978*) and infrared heaters (Businger *1963,* Rotz and Heins *1982*) are also included in the model. An insulated north wall covered with high-solar-reflectance, low-thermal-emittance material can also be simulated by merely using only the area of the cover that actually participates in energy exchange. By judicious choice of the parameters governing natural ventilation, even removal of the greenhouse cover can be modeled. By proper selection of the thermal

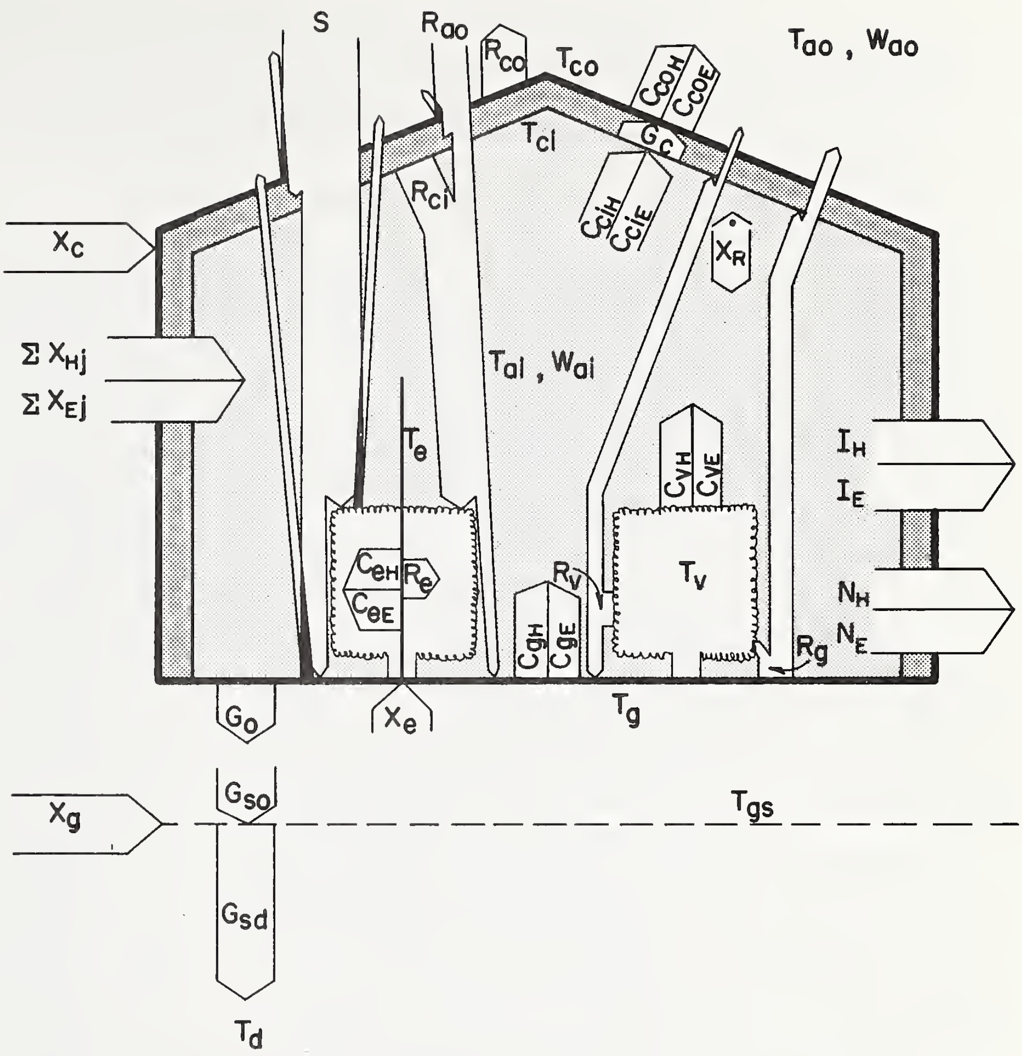

Figure 12.
Schematic illustration of a type 14 complicated greenhouse showing all the energy fluxes considered by the type 14 model. The direction of the arrows is the direction of positive flow.

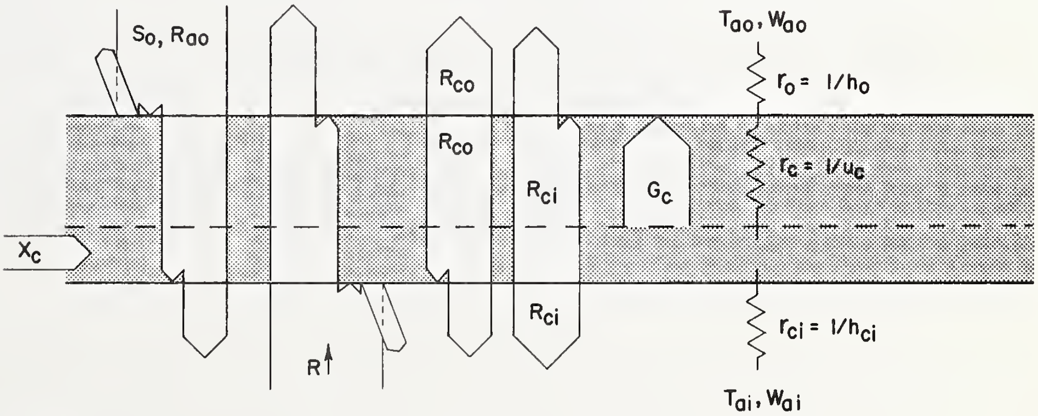

Figure 13.
Cross section of the cover of a type 14 complicated greenhouse.

capacitance and conductance properties of layers of materials beneath the greenhouse, a solar still, shallow-pond solar collector, swimming pool, or an aquaculture pond also can be simulated. The parameters needed for simulating several of these different structures are provided in table 1.

The following notations will be used:

- A area (m^2)
- B soil heat conduction transfer functions
- C convection (W)
- D density (kg/m^3)
- E evapotranspiration (kg/s)
- F angle factor for thermal radiation exchange
- G conduction in soil or cover (W)
- I infiltration through cracks and interstices (W)
- J number of external devices
- K mass transfer coefficient ($kg/m^2 \cdot s$)
- L leaf area index
- M mass flow rate when subscript affixed (kg/s); maximum number of soil heat conduction transfer functions when no subscript affixed
- N natural ventilation through ventilators (W); number of rows per curtain heat exchanger
- P pressure (kPa) or parameter
- Q fossil energy use rate (W)
- R thermal radiation (W)
- S solar radiation (W/m^2)
- T temperature (°C)
- U overall heat transfer coefficient ($W/m^2 \cdot C$)
- V modified angle factor that accounts for direct plus reflected thermal radiation
- W humidity ratio (kg H_2O/kg air)
- X energy from external device (W)
- Y shortening variable
- Z soil depth (m)
- b coefficients
- c heat capacity at barometric pressure ($J/kg \cdot °C$)
- f fraction of energy that is radiant
- h heat transfer coefficient ($W/m^2 \cdot °C$)
- k thermal conductance ($W/m^2 \cdot °C$)
- ℓ length of a row of vegetation (m)
- n number
- p water vapor pressure (kPa)
- r resistance of constant-ratio soil-conduction transfer functions
- s row spacing (m)
- t time(s)
- u velocity of air movement (m/s) (For infiltration the units are mm/s and for natural ventilation they are greenhouse volumes per hour.)
- v greenhouse volume (m^3)
- w width of row (m)
- x height of curtain heat exchanger (m)
- y height of a row of vegetation (m)
- z average height of greenhouse (m)
- Δ increment of
- α absorptance
- β angle for thermal radiation angle factor derivations (rad)
- γ control variable
- δ slope with respect to temperature ($°C^{-1}$)
- ϵ emittance
- κ thermal conductivity ($W/m \cdot °C$)
- λ latent heat of vaporization (J/kg)
- ρ reflectance
- σ Stefan-Boltzmann constant ($W/m^2 \cdot K^4$)
- Σ sum or shortening variable consisting of sum of previous soil heat flux and temperature terms
- τ transmittance

Subscripts are as follows:

A	on an area basis
E	latent heat component
H	sensible heat component
I	for infiltration
N	for deepest soil layer, or maximum
M	for natural ventilation
R	for thermal radiation or radiant heater
S	for solar radiation
T	transpiration
W	for humidity ratio
a	air
ag	air-soil
ai	inside air
ao	outside air
ac	from air to cover
c	cover
cc	from cover to cover
ce	from cover to exchanger
cg	from cover to ground
ci	inside cover
cii	inside surface of inside cover
cio	outside surface of inside cover
co	outside cover
coi	inside surface of outside cover
coo	outside surface of outside cover
cv	from cover to vegetation
d	deep soil
e	curtain heat exchanger
ec	from exchanger to cover
ee	from exchanger to exchanger
eg	from exchanger to soil
ev	from exchanger to vegetation
f	fluid
g	soil or ground
gc	from soil to cover
ge	from soil to exchanger
goc	from outside soil to cover
gv	from soil to vegetation
gs	soil storage
i	inside
j	index for external devices and thermal radiation terms
k	index for thermal radiation terms
ℓ	left; index for thermal radiation terms
m	index for soil heat conduction transfer functions
n	index for row spacing
o	outside
p	for powered air circulation
r	right
s	refers to row spacing or to storage layer in soil
so	refers to the soil surface side of the soil storage layer
sd	refers to the deeper side of the soil storage layer
v	vegetation
vc	from vegetation to cover
ve	from vegetation to exchanger
vg	from vegetation to soil when referring to angle factors or average of vegetation and soil when referring to reflectance
vs	refers to area of vegetation that absorbs radiation
vv	from vegetation to vegetation
x	external device
xc	external device to cover
xg	external device to soil
0	intercept, control variable equals 0, or soil surface
1	refers to the topmost or first member of a series, such as a series of soil layers, or coefficients; or refers to the value of the control variable. Higher numbers identify higher members of a series.

Superscripts are as follows:

*	indicates saturated condition
o	old, from a previous condition
$\uparrow$	upgoing
$\downarrow$	downcoming

Table 1.—Possible values of the parameters for a type 14 complicated greenhouse to simulate 4 greenhouse types, a solar still, a solar collector, and an aquaculture rearing pond

		Greenhouse						
Param. No.	Symbol	Fiberglass[1]	Glass with thermal screen[2]	Double-film thermal screen with curtain exchan.[3]	Fluid roof with curtain heat exchan.[4]	Glass solar still[5]	Shallow pond solar coll.[6]	Solar-heated aquaculture pond[7]
1	J	2	2	1	0	0	0	0
2	A_c	[8]1.6	[8]1.6	[8]1.6	[8]1.6	[9]1.1	[10]1.0	[10]1.0
3	A_g[11]	1	1	1	1	1	1	1
4	v_{ai}[12]	3	3	3	3	0.13	0.01	0.3
5	ℓ[11]	1	1	1	1	1	1	1
6	s[13]	1	1	1	1	1	1	1
7	N_e	1	1	20	1	1	1	1
8	x_e	0	0	2	2	0	0	0
9	ρ_v	[14]0.13	[14]0.13	[14]0.13	[14]0.13	1.0	1.0	1.0
10	ρ_g	[14]0.16	[14]0.16	[14]0.16	[14]0.16	[15]0.02	[16]0.11	[15]0.02
11	ϵ_v	[17]0.98	[17]0.98	[17]0.98	[17]0.98	0	0	0
12	ϵ_g	[17]0.95	[17]0.95	[17]0.95	[17]0.95	[18]0.96	[18]0.96	[18]0.96
13	ϵ_e	0	0	[19]0.95	[20]0.71	0	0	0
14	c_{xc}	0	0	0	[21]4,190	0	0	0
15	c_{xg}	0	0	[21]4,190	[21]4,190	0	0	0
16	c_{xe}	0	0	[21]4,190	[21]4,190	0	0	0
17	b_1[22]	5.7	5.7	5.7	5.7	5.7	5.7	5.7
18	b_2[22]	3.8	3.8	3.8	3.8	3.8	3.8	3.8
19	b_3[23]	1.5	1.5	1.5	1.5	1.5	1.5	1.5
20	b_4[23]	0.33	0.33	0.33	0.33	0.33	0.33	0.33
21	b_5	[24]9.0	[24]9.0	[24]9.0	[24]9.0	0	0	[25]37
22	b_6	[24]4.5	[24]4.5	[24]4.5	[24]4.5	0	0	[25]0
23	b_7	[24]0	[24]0	[24]0	[24]0	0	0	[25]56
24	b_8[26]	100	100	100	100	1.E4	1.E4	1.E4
25	b_9[26]	20,300	20,300	20,300	20,300	1.E5	1.E5	1.E5
26	b_{10}[26]	17	17	17	17	10	10	10
27	r_g	[27]100	[27]100	[28]400	[27]100	[21]0.0	[21]0.0	[21]0.0
28	h_{p1}[29]	6	6	6	6	0	0	0
29	X_{RM}	0	0	0	0	0	0	0
30	f	0	0	0	0	0	0	0
31	$\tau_{Sco}0$	[30]0.66	[31]0.88	[32]0.89	[33]1.00	[31]0.88	[34]0.91	[32]0.89
32	$\tau_{Sco}1$	0	0	0	0	0	0	[33]1.00
33	$\tau_{Sci}00$	[33]1.00	[33]1.00	[32]0.89	[35]0.78	[33]1.00	[33]1.00	[32]0.89
34	$\tau_{Sci}01$	0	[36]0.00	[36]0.00	0	0	0	[33]1.00
35	$\tau_{Sci}10$	0	0	0	[35]0.33	0	0	0
36	$\tau_{Sci}11$	0	0	0	0	0	0	0
37	$\alpha_{Sco}0$	[30]0.24	[31]0.02	[32]0.01	[33]0.00	[31]0.02	[34]0.00	[32]0.01
38	$\alpha_{Sco}1$	0	0	0	0	0	0	[33]0.00
39	$\alpha_{Sci}00$	[33]0.00	[33]0.00	[32]0.01	[35]0.11	[33]0.00	[33]0.00	[32]0.01

Table 1.—Possible values of the parameters for a type 14 complicated greenhouse to simulate 4 greenhouse types, a solar still, a solar collector, and an aquaculture rearing pond—Continued

		Greenhouse						
Param. No.	**Symbol**	**Fiber-glass[1]**	**Glass with thermal screen[2]**	**Double-film thermal screen with curtain exchan.[3]**	**Fluid roof with curtain heat exchan.[4]**	**Glass solar still[5]**	**Shallow pond solar coll.[6]**	**Solar-heated aqua-culture pond[7]**
40	$\alpha_{Sci}01$	0	[36]0.90	[36]0.90	0	0	0	[33]0.00
41	$\alpha_{Sci}10$	0	0	0	[35]0.56	0	0	0
42	$\alpha_{Sci}11$	0	0	0	0	0	0	0
43	U_c00	[37]160	[38]330	[39]3.5	[40]9.1	[38]330	[41]2500	[39]3.5
44	U_c01	0	[42]3.5	[39]1.8	0	0	0	[43]1.E4
45	U_c10	0	0	0	[40]320	0	0	0
46	U_c11	0	0	0	0	0	0	0
47	$\tau_{Rco}0$	[44]0.07	[45]0.03	[46]0.80	[33]1.00	[45]0.03	[47]0.43	[46]0.80
48	$\tau_{Rco}1$	0	0	0	0	0	0	[33]1.00
49	$\tau_{Rci}00$	[33]1.00	[33]1.00	[46]0.80	[48]0.03	[33]1.00	[33]1.00	[46]0.80
50	$\tau_{Rci}01$	0	[20]0.00	[20]0.00	0	0	0	[33]1.00
51	$\tau_{Rci}10$	0	0	0	[48]0.00	0	0	0
52	$\tau_{Rci}11$	0	0	0	0	0	0	0
53	$\epsilon_{coo}0$	[44]0.87	[45]0.90	[46]0.12	[33]0.00	[45]0.90	[47]0.47	[46]0.12
54	$\epsilon_{coo}1$	0	0	0	0	0	0	[33]0.00
55	$\epsilon_{coi}0$	[44]0.87	[45]0.90	[46]0.12	[33]0.00	[45]0.90	[47]0.47	[46]0.12
56	$\epsilon_{coi}1$	0	0	0	0	0	0	[33]0.00
57	$\epsilon_{cio}00$	[33]0.00	[33]0.00	[46]0.12	[48]0.87	[33]0.00	[33]0.00	[46]0.12
58	$\epsilon_{cio}01$	0	[20]0.71	[20]0.71	0	0	0	[33]0.00
59	$\epsilon_{cio}10$	0	0	0	[48]0.90	0	0	0
60	$\epsilon_{cio}11$	0	0	0	0	0	0	0
61	$\epsilon_{cii}00$	[33]0.00	[33]0.00	[46]0.12	[48]0.87	[33]0.00	[33]0.00	[46]0.12
62	$\epsilon_{cii}01$	0	[20]0.84	[20]0.84	0	0	0	[33]0.00
63	$\epsilon_{cii}10$	0	0	0	[48]0.90	0	0	0
64	$\epsilon_{cii}11$	0	0	0	0	0	0	0
65	$b_{11}00$	[49]0.12	[50]0.12	[51]0.06	[52]0.12	[53]0.00	[53]0.00	[54]0.06
66	$b_{11}01$	[49]0.12	0	0	0	0	0	
67	$b_{11}10$	0	[55]0.06	[55]0.03	0	0	0	[53]0.00
68	$b_{11}11$	0	0	0	0	0	0	0
69	$b_{12}00$	[50]0.039	[50]0.039	[51]0.02	[52]0.039	[53]0.00	[53]0.00	[54]0.039
70	$b_{12}01$	[50]0.039	0	0	0	0	0	0
71	$b_{12}10$	0	[55]0.02	[55]0.01	0	0	0	[53]0.00
72	$b_{12}11$	0	0	0	0	0	0	0
73	$b_{13}00$	[56]0.00	[56]0.00	[56]0.00	[56]0.00	[53]0.00	[53]0.00	[56]0.00
74	$b_{13}01$	[49]0.23	0	0	0	0	0	0
75	$b_{13}10$	0	[56]0.00	[56]0.00	0	0	0	[56]0.00
76	$b_{13}11$	0	0	0	0	0	0	0

Footnotes for Table 1

[1] Conventional greenhouse glazed with single layer of fiberglass. Tomato crop growing in sand.

[2] Single-layer glasshouse equipped with thermal screen which can be drawn at night (when $\gamma_{ci} = 1$) to conserve energy. Thermal screen has properties of polyester–aluminum–vinyl laminate (Stauffer Chemical), with reflective polyester side facing inward. Tomato crop growing in sand.

[3] Double polyethylene greenhouse equipped with polyester–aluminum–vinyl (polyester outside) thermal screen and black polyethylene curtain heat exchangers which can be drawn at night (when $\gamma_{ci} = \gamma_e = 1$). Reflective polyester side faces upward to raise curtain temperature and thus reduce condensation (Bailey *1981*). Floor is porous concrete over saturated-gravel energy-storage layer over polystyrene (Mears et al. *1977,* Kimball *1983*). Floral crop growing in containers on floor, but properties of floor assumed to be dominated by the porous concrete.

[4] Fluid-roof greenhouse consisting of $CuCl_2$ flowing in hollow-core polycarbonate similar to roof described by Van Bavel et al. (*1981*). Curtain heat exchangers constructed from clear-polyester–aluminum–black-vinyl laminate (Stauffer Chemical) and installed with highly solar reflective side out (to avoid shading the plants). Used to collect excess heat in daytime and heat greenhouse at night. Tomato crop growing in sand.

[5] Single-glass panes over 2.5 cm of water over 2.5 cm of Styrofoam.

[6] Water 10 cm deep in polyethylene bag insulated on back with 2.5 cm of Styrofoam. As described by Gopffarth et al. (*1968*), bag consists of black polyethylene back and clear polyethylene top. Tedlar (polyvinylfluoride, E. I. du Point de Nemours & Co.) film 1 cm above top provides insulation from ambient air.

[7] As used by Brooks and Kimball (*1983*). Water 1.5 m deep over clay loam. Cover is removable, double-layer polyethylene, with 30-cm air gap between bottom layer and water surface. Cover removed by making it transparent and increasing natural ventilation when $\gamma_{co} = \gamma_{ci} = \gamma_N = 1$.

[8] Cover-to-soil ratio of large single greenhouse is typically 1.6 (Businger *1963*).

[9] Glass planes leaned against each other with no sidewall.

[10] Cover films stretched horizontally over water.

[11] Unit area and length. For actual areas, scale up parameters 2, 3, 4, and 5.

[12] For unit area, volumes are also average heights of the structures.

[13] A 1.0-m row spacing, together with values of 0.8 and 0.2 m for the height and width of the row (inputs 7 and 8), gives leaf area index of 2.0. For nongreenhouse structures, inputs 7 and 8 should be set to 0.

[14] Measured in the USWCL greenhouse number 2 with Spectran Model 4048 radiometer. Soil (moist sand) values from 9 August 1978 and vegetation values from 29 September 1978 with full tomato canopy.

Footnotes for Table 1—Continued

[15]From Fresnel's law (Duffie and Beckham *1974*, p. 108), with 30° as average angle of incidence and 1.332 as index of refraction for water (Hodgman et al. *1962*, p. 3073).

[16]From solar trànsmittance value of 0.89 (Godbey et al. *1979*), assuming absorptance of clear polyethylene is 0.0.

[17]From Idso et al. (*1969*) for Superstition sand and tomatoes.

[18]From Konrat'yev (*1965*, p. 32) for water. For solar collector with water in a polyethylene bag, emittance assumed to be effectively that of water due to high transmittance of polyethylene for thermal radiation.

[19]From thermal reflectance for black polyethylene of 0.05 (Bailey *1981*), and assuming that water inside will make partially transparent black polyethylene behave as though nearly black in thermal region.

[20]From Baily (*1981*) for polyester with aluminized face laminated to PVC (Peerless film TS).

[21]Water.

[22]From McAdam's expression (Duffie and Beckman *1974*, p. 83).

[23]From ASHRAE (*1972*, p. 40).

[24]The b_5 value of 9.0 (volumes/h)/(m/s) is from Maher and O'Flaherty (*1973*) using data of Whittle and Lawrence (*1960*). Modeling data of Kozai and Sase (*1978*) about 3 times larger than Whittle and Lawrence's, but Kozai and Sase did compute changes with ΔT. The b_6 value of 4.5 comes from the Kozai and Sase data divided by 3. Value of 0.0 used for b_7 because assumed, for this case, that the other 2 terms account for all natural ventilation. Remember that control variable γ_N (input 13) actually controls opening of any ventilators, and therefore that it should be forced to zero for no ventilators or closed ventilators.

[25]These values can be used to simulate complete removal of greenhouse cover. Calculated from Equations 14–105 and 14–106 with $D_{ao} = 1.2$ kg/m^3, $c_{ao} = 1{,}015$ J/kg•°C, $A_c = 1$ m^2, and v_{ai} 0.3 m^3.

[26]Greenhouse values from tomato data of B. A. Kimball et al. (*1980*). Values for nongreenhouse structures force high values for stomatal resistance.

[27]Estimated for moist soil with about 10 percent visible dry spots.

[28]Estimate based on dry porous concrete floor and nondry soil surfaces in containers.

[29]As measured with hot film anemometer in USWCL greenhouse, average air velocity was about 0.3 m/s from circulation fans and from cooling system fans (when the circulation fans were off). The 6 W/m^2•°C value for greenhouses was obtained using 0.3 m/s in McAdam's expression.[22]

[30]Solar transmittance of fiberglass was measured[14] at 0.66. Absorptance obtained from transmittance, assuming reflectance of 0.10.

Footnotes for Table 1—Continued

[31]Solar transmittance for glass of 0.88 is from Godbey et al. (*1979*). Absorptance obtained from transmittance, assuming reflectance of 0.10 (Duffie and Beckman *1974*, fig. 6.1.3).

[32]Solar transmittance for single layer of polyethylene is 0.89. Absorptance obtained from transmittance, assuming reflectance of 0.10.

[33]Imaginary cover made transparent.

[34]Solar transmittance for Tedlar of 0.91 is from Godbey et al. (*1979*). Absorptance obtained from transmittance, assuming reflectance of 0.09.

[35]Solar transmittance and absorptance of 0.33 and 0.56, respectively, for hollow-core polycarbonate filled with 3 percent $CuCl_2$ are averages of the visible and near infrared values from Van Bavel et al. (*1981*), assuming solar spectrum is half visible and half near infrared. Solar transmittance of hollow-core polycarbonate with empty channels measured with Isco spectral radiometer averaged 0.78 for the solar spectrum. Absorptance for empty polycarbonate obtained from transmittance, assuming reflectance of 0.11.

[36]Solar transmittance of clear-polyester–aluminum–black-vinyl laminate is 0. Absorptance estimated to be 0.15 on polyester side and 0.90 on vinyl side.

[37]Thermal conductance of single layer fiberglass of 160 $W/m^2 \cdot {}^\circ C$ calculated from manufacturer-supplied value of 0.16 $W/m \cdot {}^\circ C$ for thermal conductivity, measured thickness of 1.1 mm, and corregation factor of 1.09.

[38]Thermal conductance for single layer glass of 330 $W/m^2 \cdot {}^\circ C$ calculated from thermal conductivity of 1.05 $W/m \cdot {}^\circ C$ (Duffie and Beckman *1974*) and thickness of 3.18 mm.

[39]Thermal conductance of 3.5 $W/m^2 \cdot {}^\circ C$ for air spaces between glass and thermal screen and between polyethylene layers is from ASHRAE (*1972*, p. 359) for 10-cm-thick horizontal space with effective emittance of 0.2 and 15°C temperature difference. For 2 air spaces of double polyethylene plus thermal screen, value for 1 space was reduced by one-half.

[40]Thermal conductance of hollow-core polycarbonate calculated assuming parallel resistances of wall material and fluid in series with inner and outer wall resistances. Dimensions: total thickness, 6 mm; wall thicknesses, 0.6 mm; channels, 4.8 mm × 4.8 mm. Thermal conductivity values used were 0.192 (Cadillac Plastic *1976*), 0.596, and 0.026 (Duffie and Beckman *1974*) for polycarbonate, water, and air, respectively. Overall thermal conductances of the materials are 67 and 9.1 $W/m^2 {}^\circ C$ when channels filled with stagnant water and air, respectively. Conductance of 1 outer or inner wall layer is 320 $W/m^2 {}^\circ C$. For this example, assumed that channels will be drained and filled with stagnant air when $CuCl_2$ solution not being circulated ($\gamma_f = 0$). However, when fluid being circulated ($\gamma_f = 1$), only resistance is that of a single wall layer.

[41]Thermal conductance for Tedlar (polyvinylfluoride) of 2500 $W/m^2 \cdot {}^\circ C$ calculated from thermal conductivity value for polyvinylchloride of 0.19 $W/m \cdot {}^\circ C$ and thickness of 76 μm (Cadillac Plastic *1976*).

[42]Thermal conductance of 6.7 $W/m^2 \cdot °C$ between glass and black vinyl of thermal screen is from ASHRAE (*1972* p. 359) for 10-cm-thick horizontal space with effective emittance of 0.8[20 45] and 15°C temperature difference.

[43]Large value of 1.E4 $W/m^2 \cdot °C$ used to simulate rapid heat transfer across covers which have been removed and are now imaginary (when $\gamma_{ci} = 1$).

[44]Thermal transmittance for fiberglass of 0.07 is from Godbey et al. (*1979*). Emittance obtained from transmittance, assuming reflectance of 0.06.

[45]Thermal transmittance for glass of 0.03 is from Godbey et al. (*1979*), and emittance of 0.90 from Sellers (*1965,* p. 41).

[46]Thermal transmittance for polyethylene of 0.80 is from Godbey et al. (*1979*). This value likely to be more representative of 101-μm (4-mil) films, which might be used as greenhouse covering, than 0.85 value of Bailey (*1981*). Emittance value of 0.12 is from Bailey (*1981*) and results in reflectance of 0.08. This reflectance is higher than the 0.03 listed by Bailey, but his value contains measurement errors of both the transmittance and emittance determinations.

[47]Thermal transmittance for Tedlar of 0.43 is from Godbey et al. (*1979*). Emittance obtained from transmittance, assuming reflectance of 0.10.

[48] Godbey et al. (*1979*) found thermal transmittance of 1.6-mm sheet of polycarbonate to be 0.06. Therefore, thermal transmittance for hollow-core polycarbonate with air in the channels should be about 0.03, and reflectance assumed to be about 0.10. When filled with $CuCl_2$ solution, transmittance would be 0.

[49] Based on CO_2 infiltration tests of 3 August 1978 with the USWCL fiberglass greenhouses, average b_{11} value was 0.12 (mm/s)/(m/s) for the closed greenhouses. Value for house (#2) with only evaporative cooler pads to close the air intake was 0.71. Small circulation fans were on in all greenhouses. When large cooling-system fans were on in the closed greenhouses, average b_{13} to account for the additional infiltration was 0.23.

[50] From Okada and Takakura (*1973*) for glasshouse.

[51] American Society of Agricultural Engineers (*1982*) lists infiltration rate of double polyethylene greenhouse as half that of new glasshouse.

[52] Assume equivalent to that of new glasshouse.

[53] Assume negligible infiltration.

[54] Assume that double-polyethylene-covered aquaculture pond equivalent to double-polyethylene-covered greenhouse.

[55] Assume thermal screen reduces infiltration by 50 percent.

[56] Zero used, assuming all infiltration accounted for by other terms.

Energy balance equations

Referring to figures 12 and 13, the energy balances are—

For the outer greenhouse cover

$$S_{co} + R_{con} + G_c - C_{coH} - C_{coE} = 0 \tag{14–1}$$

For the inner greenhouse cover

$$S_{ci} + R_{cin} - G_c + C_{ciH} + C_{ciE} + X_c = 0 \tag{14–2}$$

For the vegetation

$$S_v + R_{vn} - C_{vH} - C_{vE} + X_{Rv} = 0 \tag{14–3}$$

For the soil surface

$$S_g + R_{gn} - C_{gH} - C_{gE} + X_{Rg} - G_0 = 0 \tag{14–4}$$

For the curtain heat exchanger

$$R_{en} - C_{eH} - C_{eE} + X_e = 0 \tag{14–5}$$

For the greenhouse air

$$\begin{aligned} &C_{gH} + C_{gE} + C_{vH} + C_{vE} + C_{eH} + C_{eE} - C_{ciH} - C_{ciE} - I_H - I_E - N_H \\ &- N_E + \sum_j X_{Hj} + \sum_j X_{Ej} + X_{Ra} = 0 \end{aligned} \tag{14–6}$$

The latent energy or moisture balance for the greenhouse air is

$$C_{gE} + C_{vE} + C_{eE} - C_{ciE} - I_E - N_E + \sum_j X_{Ej} = 0 \tag{14–7}$$

The energy balance for a soil storage layer is

$$G_{s0} + X_g - G_{sd} = 0 \tag{14–8}$$

The individual fluxes in equations 14–1 through 14–8 are defined in detail in the following sections. The equations contain the unknown temperatures T_{co}, T_{ci}, T_v, T_{go} T_e, T_{ai}, and T_{gs}, as well as the unknown air humidity ratio, W_{ai}. These unknowns are computed by subroutine CGH as solutions to equations 14–1 through 14–8. Refer to the code table in appendix E and the special forms in appendix D to see how the many parameters and inputs are given to subroutine CGH.

Greenhouse, vegetation, and curtain heat exchanger geometry

Because the geometry of crops growing in greenhouses is exceedingly complex, several first-order approximations are made. Referring to figures 14 through 16, the crop is assumed to be growing directly in the soil in rows spaced s meters apart and ℓ meters long, where ℓ and s are parameters. If ℓ and s are set equal to zero by the user, the program will reset them to 0.1 and 1.0 m, respectively.

The number of rows of vegetation, n_v, is computed from

$$n_v = A_g/(\ell s) \tag{14–9}$$

The height of the vegetation, y, and the row width, w, are inputs; so the user can "grow" a crop using these two variables from a type 12 time function or similar device. If w or y is given as zero, the program will set it to 0.001 m, thus providing a physically insignificant, yet nonzero amount of vegetation. Ignoring end effects, the area of vegetation is computed from

$$A_v = 2n_v\ell(w+y) \tag{14–10}$$

The area of vegetation which absorbs solar radiation, A_{vS}, is assumed to be the top of rows plus the upper half of one side.

$$A_{vS} = n_v\ell(w+y/2\ ) \tag{14–11}$$

The upper limit to A_{vS} is the soil area, A_g. Also, the area of soil that receives solar radiation is assumed to be $A_g - A_{vS}$.

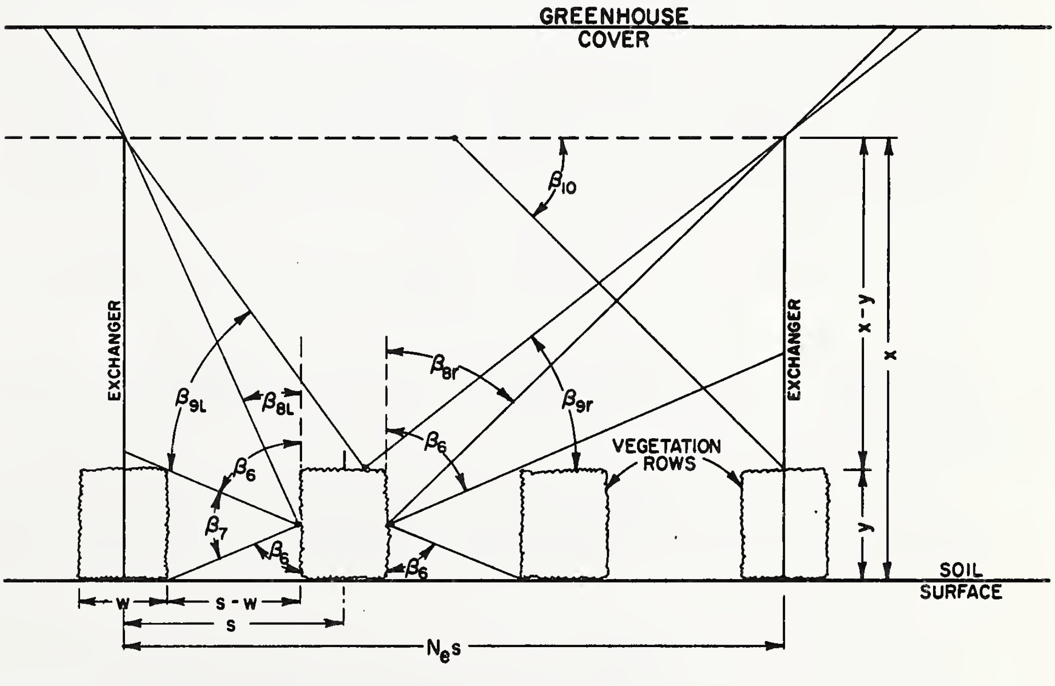

Figure 14.
Cross section through greenhouse, with vegetation rows and curtain heat exchangers spaced N_e rows apart. The β's are angles which illustrate the angle factors for thermal radiation emitted from the exchangers.

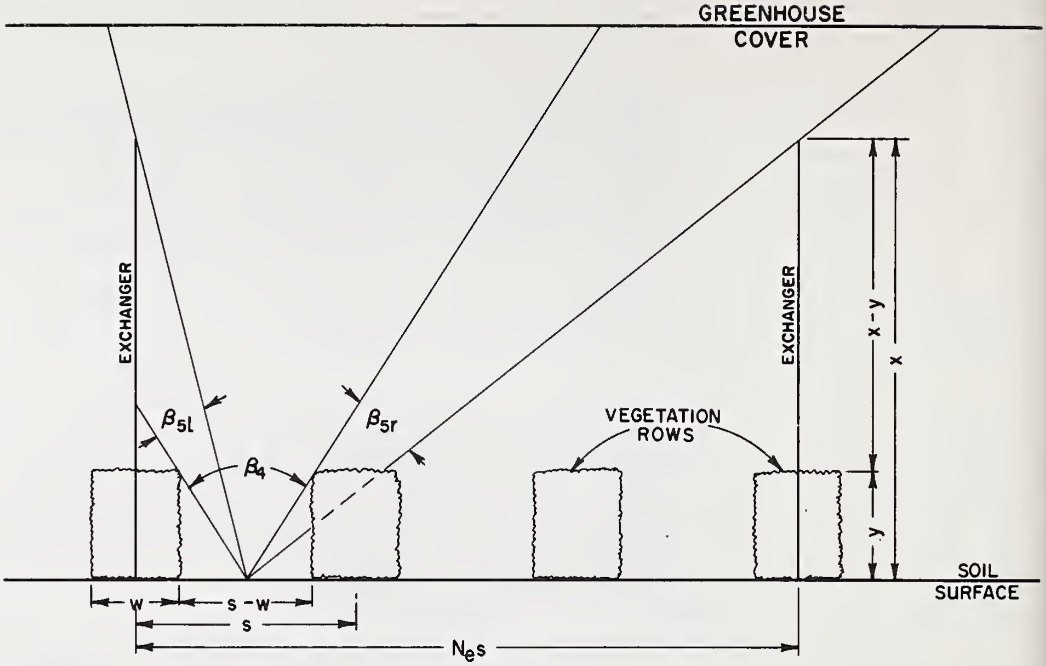

Figure 15.
Cross section through greenhouse with vegetation rows and curtain heat exchangers spaced N_e rows apart. The β's are angles which illustrate the angle factors for radiation emitted from the soil surface.

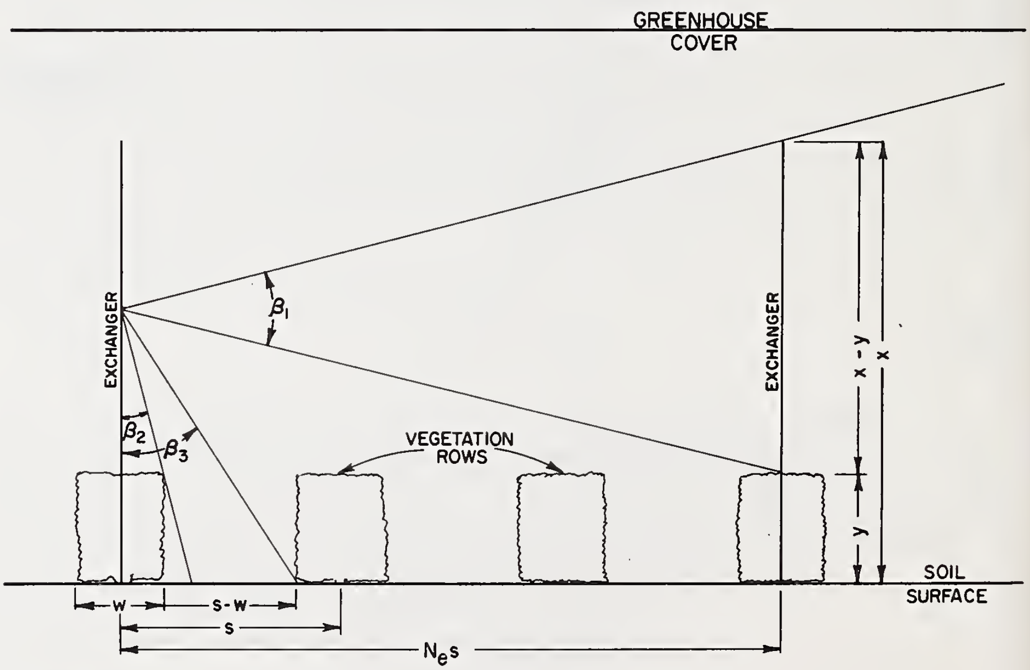

Figure 16.
Cross section through greenhouse with vegetation rows and curtain heat exchangers spaced N_e rows apart. The β's are angles which illustrate the angle factors for thermal radiation emitted from the vegetation ($\beta_6 - \beta_9$) and from the cover (β_{10}). The dashed line indicates the effective height of the cover.

The average reflectance of the soil and vegetation for solar radiation, ρ_i, is computed from

$$\rho_{vg} = (\rho_v A_{vS} + \rho_g (A_g - A_{vS})) / A_g \tag{14–12}$$

The curtain heat exchangers' area is a prominent feature in figures 14 through 16. The exchangers are an experimental device (Simpkins et al. *1978*) for inexpensively increasing the exchange of energy between the greenhouse and a source of hot or cold liquid. They consist of a sheet of plastic film draped over a liquid distribution pipe. The liquid runs down the inside between the film and pipe and is drained away at the bottom by some means. It is assumed that the curtains do not absorb any significant amount of solar radiation. In practice, this assumption would usually be satisfied because (1) the curtains are only used at night and are stored by some mechanism during the day, (2) the curtains are made of a material with a high reflectance for solar radiation, or (3) the curtains are shorter than the crop for much of a cropping cycle.

To model the storage of curtains during the daytime, the height of the curtain, x, is the product of the parameter maximum height, x_e, and an input control variable, γ_e, that can vary from 0 to 1 and can be supplied by a type 12 time clock or similar device. To prevent any mathematical problems with zero denominators, the program assigns a minimum value of 1 mm to x. Thus, the greenhouse always has curtain heat exchangers, but they can be made so small as to be insignificant. The user must also specify the number (not zero) of vegetation rows per individual curtain, N_e. Then, the program computes the total exchanger area, A_e, from

$$A_e = 2 n_v \ell x / N_e \tag{14–13}$$

The curtains are assumed to be positioned in the middle of double rows, as illustrated in figure 14. This placement frees the isles for workers and negates the need for moving the curtains, but they could be too cold or hot for maximum production of the adjacent rows. As far as the energy exchange is concerned, the assumption about placement mostly affects angle factors for thermal radiation. These can be estimated only crudely, at best; and the the angle factors for between-row placement would not be greatly different from those for within-row placement, which are derived in the next section.

Changing greenhouse cover properties

The characteristics of the greenhouse cover can be changed by varying the value of three control variables, γ_{co}, γ_{ci}, and γ_f. For example, the user can simulate shading the greenhouse in the summertime with an outside coating of whitewash by changing the outer cover control variable, γ_{co}, with a type 12 time function (calendar). Likewise, the drawing of a thermal screen at night can be simulated by changing γ_{ci} with another type 12 time function (clock). The properties of the inside cover also can be changed by γ_f, the control variable for the flow of any fluid in the roof.

To accomplish the transition from one cover condition to another, the user must supply at least two sets of cover parameters: one set for when $\gamma=0$ and the other for when $\gamma=1$. Then subroutine CGH performs a linear interpolation from the set for $\gamma=0$ to the other set for $\gamma=1$, as indicated by the equation

$$P=(1-\gamma)P_0+P_1 \tag{14–14}$$

where P is the property value for the particular simulation time, and P_0 and P_1 are the values of the cover parameters corresponding to $\gamma=0$ and $\gamma=1$, respectively.

Some of the cover properties can change with two control variables. For example, the thermal conductance, U_c, can change with both γ_f and γ_{ci} (see appendix E). For these properties the user must supply four sets of parameters, and then the program performs a linear interpolation from one set to another according to

$$P=(1-\gamma_f)(1-\gamma_{ci})P_{00}+(1-\gamma_f)\gamma_{ci}P_{01}+\gamma_f(1-\gamma_{ci})P_{10}+\gamma_f\gamma_{ci}\,P_{11} \tag{14–15}$$

where P is the property value used for the particular simulation and P_{00}, P_{01}, P_{10}, and P_{11} are the values of the parameters corresponding to $\gamma_f=\gamma_{ci}=0$; $\gamma_f=0$, $\gamma_{ci}=1$; $\gamma_f=1$, $\gamma_{ci}=0$; and $\gamma_f=\gamma_{ci}=1$, respectively. The parameters for several different covers are provided in table 1.

Solar energy

The most important energy flux in a greenhouse is, of course, the solar radiation absorbed by the vegetation, S_v, because it is this energy that drives photosynthesis and, ultimately, the marketable yield. This program computes S_v from

$$S_v=S_oA_{vS}\tau_{Sco}\tau_{Sci}(1-\rho_v) \tag{14–16}$$

where S_o is the solar radiation on a horizontal surface outside the greenhouse (input 1), τ_{Sco} and τ_{Sci} are the transmittances of the outer and inner cover for solar radiation, and ρ_v is the reflectance of the vegetation.

The solar radiation absorbed by the soil is computed similarly:

$$S_g=S_o(A_g-A_{vS})\tau_{Sco}\tau_{Sci}(1-\rho_g) \tag{14–17}$$

The solar radiation absorbed at the outer cover, S_{co}, and that absorbed at the inner cover, S_{ci}, are computed from

$$S_{co}=S_oA_g\alpha_{Sco}(1+\tau_{Sco}\tau_{Sci}\rho_{vg}\tau_{Sci}) \tag{14–18}$$

$$S_{ci}=S_oA_g\tau_{Sco}\alpha_{Sci}(1+\tau_{Sci}\rho_{vg}) \tag{14–19}$$

where α_{Sco} and α_{Sci} are absorptances of the outer and inner cover for solar radiation.

The τ_{Sco} and α_{Sco} of the outer cover can change with γ_{co}, whereas τ_{Sci} and α_{Sci} change with both γ_f and γ_{ci}. Therefore, the user must supply two values each of τ_{Sco} and α_{Sco} and four values each of τ_{Sci} and α_{Sci} (appendix E).

Greenhouse-cover heat fluxes and characteristics

A schematic cross section of the greenhouse cover is shown in figure 13. It has an inner surface of temperatue T_{ci} and an outer surface with temperature T_{co}. Heat is transferred to the outer surface according to the equation

$$G_c = A_c U_c (T_{ci} - T_{co}) \tag{14–20}$$

where U_c is an overall transfer coefficient.

For a single-layer greenhouse cover, U_c is simply the thermal conductance of the cover material. For a multiple-layer greenhouse cover, such as a cover with a double layer of polyethylene and a thermal screen, U_c is the overall thermal conductance of the material of each layer and the insulating air layers (ASHRAE *1972*, p. 348). For a double-layer greenhouse cover, U_c can simply be the conductance of the intervening air layer, and the user can alter the internal emittances of the two layers to simulate the thermal radiation exchange of the two layers. Specifying the internal emittances is particularly useful for simulating covers made of plastics that are partially transparent to thermal radiation, such as polyethylene.

Also, figures 12 and 13 show an external energy flux, X_c. This flux represents a flow of fluid through the roof, which absorbs near-infrared radiation as proposed by Damagnez (*1976*). It is assumed that the rate of heat transfer from the bulk of the fluid is fast enough that any temperature difference between the average bulk fluid temperature and T_{ci} is negligible. Proper choice of U_c can provide insulation for the fluid from the outer surface but not from the inner. Thus, U_c is assumed to vary with both γ_f and γ_{ci}, and therefore the user must supply four values as indicated in appendix E.

Angle factors for thermal radiation exchange

The angle factor from one surface to another is defined as the fraction of the radiant energy emitted by the first surface which impinges upon the second (Gebhart *1961*, p. 99). Starting with the covers, it is assumed that they both have approximately the same area, so the angle factor between the two covers is 1.0. The inner cover is convex, so some radiation emitted by one part of the inner cover can be absorbed by another part of the inner cover. Thus, the inner cover sees itself by an amount that varies with the ratio of cover to ground or soil area. This angle factor for the inner cover seeing itself, F_{cc}, is computed from

$$F_{cc} = 1 - (A_g / A_c) \tag{14–21}$$

The outer cover is assumed to see itself by the same angle factor, F_{cc}, multiplied by the transmittance of the inner cover squared, τ_{Rci}^2, to account for absorption in two thicknesses of the inner cover material.

Next, consider the angle factor from curtain heat exchanger to the cover, F_{ec}. Referring to figure 14, the fraction of the radiation emitted by a point on the right side of the exchanger halfway between the top of the vegetation and the top of the exchanger that reaches the cover is $[(\pi - \beta_1)/2]/\pi$, where β_1 is the angle shown in radians. To a first approximation, the angle, β_1, will be constant if the point were moved up or down anywhere between the top of the vegetation and top of the ex-

changer. It is also assumed that none of the radiation emitted by the exchanger below the top of the vegetation reaches the cover. Therefore,

$$F_{ec} = \left(\frac{x-y}{x}\right)\left(\frac{\pi-\beta_1}{2\pi}\right) \quad ; x>y \tag{14–22}$$

or

$$F_{ec} = 0 \quad ; x \leq y$$

where

$$\beta_1 = 2\arctan[(x-y)/(2N_e s)] \tag{14–23}$$

If there is enough space between the rows, some of the radiation emitted by the exchanger above the rows can penetrate to the soil or ground surface. This penetration can occur for each row where $\beta_3 > \beta_2$. Thus, to a first approximation

$$F_{eg} = \left(\frac{x-y}{x}\right)\sum_{n=1}^{N_e}\frac{\beta_{3n}-\beta_{2n}}{\pi} \quad ; x>y \tag{14–24}$$

$$F_{eg} = 0 \quad ; x \leq y$$

for all positive $\beta_{3n} - \beta_{2n}$. The angles are given by

$$\beta_{2n} = \arctan\left[\frac{ns-(w/2)-(s-w)}{(x-y)/2}\right] \tag{14–25}$$

$$\beta_{3n} = \arctan\left[\frac{ns-(w/2)}{y+(x-y)/2}\right] \tag{14–26}$$

All of the radiation emitted by the exchanger below the top of the vegetation is intercepted by the vegetation. Also, by symmetry, the amount of the radiation emitted by the exchanger above the vegetation and going to the soil plus that going to the vegetation must equal the amount going to the cover. Therefore,

$$F_{ev} = \frac{y}{x} + (F_{ec} - F_{eg}) \quad ; x>y \tag{14–27}$$

$$F_{ev} = 1 \quad ; x \leq y$$

The angle factors for radiation emitted from the soil can be estimated from figure 15. Only the between-row spaces of fractional area $(s-w)/s$ view the cover with a fractional angle of approximately $(\beta_4 - \beta_{5\ell} - \beta_{5r})/\pi$. Only positive values of $\beta_{5\ell}$ and β_{5r} are included, so the β_{5r} shown in figure 15 would be set to zero. The fractional angle must be the average for all the between-row spaces between each curtain heat exchanger. Therefore,

$$F_{gc} = \left(\frac{s-w}{s}\right)\left(\frac{1}{N_e}\right)\sum_{n=1}^{N_e}\left(\frac{\beta_4 - \beta_{5\ell n} - \beta_{5rn}}{\pi}\right) \tag{14–28}$$

where $\beta_4 = 2\arctan[(s-w)/(2y)]$ (14–29)

$$\beta_{5\ell n} = \arctan\left[\frac{x}{ns-(s/2)}\right] - \arctan\left[\frac{2y}{s-w}\right] \quad (14\text{–}30)$$

$$\beta_{5rn} = \arctan\left[\frac{x}{N_e s - ns + (s/2)}\right] - \arctan\left[\frac{2y}{s-w}\right] \quad (14\text{–}31)$$

Similarly, the between-row spaces view the curtain heat exchanger with a fractional angle of $(\beta_{5\ell} + \beta_{5r})/\pi$, where again only positive angles are included. Therefore, averaging over all the between-row spaces,

$$F_{ge} = \left(\frac{s-w}{s}\right)\left(\frac{1}{N_e}\right)\sum_{n=1}^{N_s}\left(\frac{\beta_{5\ell n} + \beta_{5rn}}{\pi}\right) \quad (14\text{–}32)$$

Any radiation emitted by the soil that is not intercepted by the cover or heat exchangers must be intercepted by the vegetation. Therefore,

$$F_{gv} = 1 - F_{gc} - F_{ge} \quad (14\text{–}33)$$

The fraction of the radiation emitted by the vegetation and then absorbed by the soil can be estimated from figure 16. All radiation emitted below the rows is intercepted by the soil. Of the radiation emitted by the sides of the rows, a fraction β_6/π is intercepted by a fraction of the soil $(s-w)/s$. Therefore, the angle factor for radiation transmission from vegetation to ground is an area-weighted average:

$$F_{vg} = \frac{w + 2y(\beta_6/\pi)}{2w + 2y} \quad (14\text{–}34)$$

where $\beta_6 = \arctan[2(s-w)/y]$ (14–35)

Again referring to figure 16, the average angle by which the sides of the rows view the cover is $\beta_{8\ell} + \beta_{8r}$, and that by which the tops of the rows view the cover is $\beta_{9\ell} + \beta_{9r}$. Averaging these angles for all the rows and weighting for area yield

$$F_{vc} = \frac{y\sum_{n=1}^{N_e}(\beta_{8\ell n} + \beta_{8rn}) + w\sum_{n=1}^{N_e}(\beta_{9\ell n} + \beta_{9rn})}{\pi N_e\ (2y - 2w)} \quad (14\text{–}36)$$

where

$$\beta_{8\ell n} = \arctan\left[\frac{ns-(w/2)}{x-(y/2)}\right] \quad (14\text{–}37)$$

$$\beta_{8rn} = \arctan\left[\frac{N_e s - ns + (s-w) + (w/2)}{x-(y/2)}\right] \quad (14\text{–}38)$$

$$\beta_{9\ell n} = \arctan\left[\frac{x-y}{(n-1)s + (w/4)}\right] \quad (14\text{–}39)$$

$$\beta_{9rn} = \arctan\left[\frac{x-y}{N_e s - (n-1)s - (w/4)}\right] \quad (14\text{–}40)$$

The maximum allowable size for $\beta_{8\ell n}$ or β_{8rn} is β_6. If $x \leq y$ then $\beta_{9\ell n} = \beta_{8rn} = \pi/2$.

The vegetation also views itself as illustrated by angle β_7 in figure 16. If there were no heat exchangers, an estimate of the angle factor for viewing itself, F_{vv}, could be written $(y\beta_7)/[\pi(y+w)]$, where

$$\beta_7 = 2\arctan[(y/2)/(s-w)] \tag{14–41}$$

However, for the rows in which the heat exchanger is placed, it is assumed that the exchanger reduces the self-viewing by 0.5 if $x \geq y$ or by $(0.5x/y)$ if $x<y$.

Thus, the self-viewing is weighted for the number of rows with and without exchanger:

$$F_{vv} = \frac{(N_e-1)y\beta_7 + 0.5y\beta_7}{\pi N_e(y+w)} \quad ; x \geq y \tag{14–42}$$

$$= \frac{(N_e-1)y\beta_7 + 0.5y\beta_7 + 0.5(y-x)\beta_7}{\pi N_e(y+w)} \quad ; x<y \tag{14–43}$$

Finally, any radiation emitted by the vegetation and not intercepted by the soil, cover, or vegetation itself must impinge on the heat exchanger. Therefore,

$$F_{ve} = 1 - F_{vg} - F_{vc} - F_{vv} \tag{14–44}$$

Angle factors from the cover to the vegetation, soil, and exchanger are derived below with reference to an imaginary cover that is an infinitive plane over the crop and parallel to the soil plane. The angle factors are corrected for the actual cover seeing itself by multiplying with (A_g/A_c), derived from equation 14–21.

The angle factor from the cover to the curtain heat exchanger can be derived by referring to figure 16. For the purposes of this first approximation analysis, the effective height of the cover can be the height of the curtain heat exchangers, as indicated by the dashed line. Then,

$$\beta_{10} = arctan\left[\frac{2(x-y)}{N_e s}\right] \tag{14–45}$$

and then

$$F_{ce} = \left(\frac{A_g}{A_c}\right)\left(\frac{2\beta_{10}}{\pi}\right) \quad \text{if } x>y \tag{14–46}$$

$$F_{ce} = 0 \quad \text{if } x \leq y$$

Because the cover and soil surface are assumed to be, in effect, infinite parallel planes for thermal radiation exchange, the imaginary plane cover must view the soil as much as the soil views the cover. Therefore,

$$F_{cg} = F_{gc}(A_g/A_c) \tag{14–47}$$

Any radiation emitted by the cover and not intercepted by the soil or heat exchangers must impinge on the vegetation. Therefore,

$$F_{cv} = 1 - F_{cg} - F_{ce} - F_{cc} \tag{14–48}$$

The cover of the greenhouse also views soil and other surfaces outside the greenhouse and, of course, the sky. It is assumed that a portion of the cover equal to the soil area receives only sky radiation from above and that the rest of the cover corresponds to vertical walls which see half the sky and half the soil or other surfaces, which are at the outside air temperature. The angle factor for sky radiation impinging on the cover is computed from

$$F_{ac} = 1 + [(A_c/A_g) - 1]/2 \tag{14–49}$$

and the factor for outside soil and other surfaces impinging on the cover is computed from

$$F_{goc} = [(A_c/A_g) - 1]/2 \tag{14–50}$$

Thermal radiation

Thermal radiation fluxes emitted from the outer cover, inner cover, vegetation, and soil surface are computed using Stefan's law. Black-body radiation from the outside cover, R_{co}, is computed from

$$R_{co} = A_c\sigma(T_{co} + 273.16)^4 \tag{14–51}$$

Then, the thermal radiation emitted by the outer and inner sides of the outer cover is given by $\epsilon_{coo}R_{co}$ and $\epsilon_{coi} R_{co}$, where ϵ_{coo} and ϵ_{coi} are the emittances of the outer and inner sides of the outer cover. Similarly, the black-body radiation for the inner cover is computed from

$$R_{ci} = A_c\sigma(T_{ci} + 273.16)^4 \tag{14–52}$$

Then, the thermal radiation emited by the outer and inner sides of the inner cover is computed from $\epsilon_{cio} R_{ci}$ and $\epsilon_{cii} R_{ci}$, respectively, where ϵ_{cio} and ϵ_{cii} are the emittances of the outer and inner sides of the inner cover.

The thermal radiation emitted from the vegetation is computed from

$$R_v = A_v\sigma(T_v + 273.16)^4 \tag{14–53}$$

The thermal radiations emitted from the soil and curtain heat exchanger are computed similarly using the same equation except that the subscripts g and e would be used instead. The user must supply the emittances, ϵ_v, ϵ_g, and ϵ_c as parameters.

Much of the versatility (and complexity) of this model is accomplished by providing the capability to change the properties of the covers with control variables (equations 14–14 and 14–15). These properties include the emittances, ϵ_{coo}, ϵ_{coi}, ϵ_{cio}, and ϵ_{cii} and the transmittances of the inner and outer cover for thermal radiation, τ_{Rco} and τ_{Rci}. The outer cover properties, ϵ_{coo}, ϵ_{coi}, and τ_{Rco}, are assumed to vary with the control variable, γ_{co}, for outer cover properties. Therefore, the user must supply two

values for each of these three parameters, as discussed previously and as listed in appendix E. The inner cover properties, ϵ_{cio}, ϵ_{cii}, and τ_{Rci}, are assumed to vary both with the cover control variable, γ_{ci}, and with the fluid flow control variable, γ_f. Therefore, the user must supply four values of each of these latter three variables, as also discussed previously and listed in appendix E.

Table 1 provides values of these parameters for several different cover examples. To simulate a simple glasshouse, which is opaque to thermal radiation, the user could set the τ_{Rco}, τ_{Rci}, ϵ_{coi}, and ϵ_{cio} all equal to zero. Then, there would be thermal radiation exchange only on the outer and inner surfaces of the glass. The user could also set $\tau_{Rci} = 1.0$ and $\epsilon_{cio} = \epsilon_{cii} = 0.0$ so that an imaginary inner cover is completely transparent. To simulate a double-layer clear-polyethylene house with a black-polyethylene thermal screen that is drawn at night, the user would specify $\tau_{Rco} = \tau_{Rci} = 0.80$ (Godbey et al. *1979*) and (assuming 6 percent reflection) $\epsilon_{coo} = \epsilon_{coi} = \epsilon_{cio} = \epsilon_{cii} = 0.14$ for when $\gamma_{co} = \gamma_{ci} = 0$. Then, when $\gamma_{ci} = 1$ and the thermal screen is drawn, the specifications would be $\tau_{Rci} = 0.0$ and $\epsilon_{cio} = \epsilon_{cii} = 0.94$. If the thermal screen is made of other materials, the emittances characteristic of that material would be specified instead.

Whenever the saturation humidity ratio (defined in the next section) of any of the five surfaces is less than the humidity ratio of the adjacent air, water is assumed to condense in a film on that surface. Then, the program will use an emittance value of 0.96 for water (Kondrat'yev *1965*, p. 32) for that surface instead of the dry surface emittance values supplied as parameters by the user. Similarly, if the water condensation is detected on the outer or inner cover surfaces, then the transmittance, τ_R, of that cover surface is assumed to go to 0.0. It is further assumed that the water will not accumulate to any significant extent on the surface but, instead, will drain away in some manner. Therefore, when the temperature of the surface rises so that its saturation humidity ratio is above the humidity ratio of the adjacent air, then the surface instantly dries and the dry-surface emittance and transmittance values are used again.

Any internal air space between the outer and inner covers is assumed to be dry enough that water does not condense on the inner surface of the outside cover or on the outer surface of the inner cover. This should be a good assumption for most greenhouses, including double-layer polyethylene houses, all single-layer houses, and all greenhouses, made of "twin-wall" plastic materials.

A major class of greenhouses that would not meet this assumption comprises glass or single-layer polyethylene houses with poorly sealed thermal screens. A common problem with these houses is that water condenses on the inside of the outer surface and drips down on top of the thermal screen. Even for these houses, however, the dry internal cover assumption should not have much effect on the overall energy balances because any good thermal screen should be opaque to thermal radiation. Therefore, the main discrepancy between the model and the actual greenhouse would be that the model would predict sky radiation to be absorbed on the inner cover (thermal screen), whereas the condensate would actually absorb the sky radiation on the outer cover.

Even though the assumption is made that water does not condense on the inner side of the outer cover or the outer side of the inner cover, the effective emittances, ϵ_{coi} and ϵ_{coi}, for these sides internal to the cover can be affected by condensate on the

outer side of the outer cover or the inner side of the inner cover if the dry cover(s) is transparent to thermal radiation. Therefore, when condensate is detected on the outer side of the outer cover, the emittance for the inner side of the outer cover is computed from

$$\epsilon_{coi} = \epsilon_{coi(\mathrm{dry})} + \tau_{Rco(\mathrm{dry})}(0.96 - \epsilon_{coi(\mathrm{dry})}) \tag{14–54}$$

Similarly, when condensate is detected on the inner side of the inner cover, the emittance for the outer side of the inner cover is computed from

$$\epsilon_{cio} = \epsilon_{cio(\mathrm{dry})} + \tau_{Rci(\mathrm{dry})}(0.96 - \epsilon_{cio(\mathrm{dry})}) \tag{14–55}$$

The user-supplied parameter values for the transmittances and emittances are for the dry condition.

When a user wishes to simulate a single-cover greenhouse or complete removal of the greenhouse cover, the transmittances should be set to 1.0 and the emittances to 0.0 for the cover(s) that is to be imaginary. The program will use a transmittance of 1.0 as a flag to indicate that the cover is imaginary; and, therefore, if the cover temperature drops below the dewpoint, the program will continue to use the 1.0 transmittance and 0.0 emittance rather than water film values.

Now that the angle factors, thermal radiation fluxes, emittances, and transmittances have all been defined, the equations that describe the net thermal radiation on each surface can be written. For the outer cover,

$$\begin{aligned} R_{con} = {} & \epsilon_{coo}[F_{ac}A_gR_{ao} + F_{goc}A_gR_{go} - R_{co}] \\ & + \epsilon_{coi}[-R_{co} + \epsilon_{cio}R_{ci} + \tau_{Rci}R^{\uparrow} + \epsilon_{coi}\rho_{cio}R_{co}] \end{aligned} \tag{14–56}$$

The sky radiation, R_{ao} (W/m^2), is input 2 for subroutine CGH, and it will generally be supplied by output 21 of a type 1 reader. It is not routinely measured by the National Weather Service, but it can be calculated from air temperature and vapor pressure data using the method of Idso (*1981*) for clear skies or of Kimball et al. (*1982*) for cloudy skies. The second term accounts for the radiation from soil outside the greenhouse, R_{go} (W/m^2). It is assumed to be black-body radiation at outside air temperature:

$$R_{go} = \sigma(T_{ai} + 273.16)^4 \tag{14–57}$$

In equation 14–56 the terms in the first set of brackets are for the radiation exchanges on the outside of the outer cover. They are the sky radiation, (plus) the outside soil radiation, and (minus) the radiation emitted by the outer cover. The terms in the second set of brackets are for the radiation exchanges occurring at the inside of the outer cover. They are (minus) the radiation emitted by the inside of the outer cover, (plus) radiation from the inner cover, (plus) radiation emitted upward from surfaces below the cover, $R^{\uparrow}$, and then transmitted through the inner cover, and (plus) radiation emitted by the outer cover and then reflected back by the outside of the inner cover.

Equation 14–56 and the ones that follow contain first-order reflection terms. In some practical cases, ignoring the first-order reflection caused a 20 percent error in net

radiation prediction; so the first-order reflections are included. Second-order and higher order reflections are ignored, however.

For the inner cover

$$R_{cin} = \epsilon_{cio}[(F_{ac}A_gR_{ao} + F_{goc}A_gR_{go})\tau_{Rco} + \epsilon_{coi}R_{co} - R_{ci} + \epsilon_{cio}\rho_{coi}R_{ci}] + \epsilon_{cii}[R^{\uparrow} - R_{ci}] \quad (14\text{–}58)$$

Here the terms in the first set of brackets are for the exchanges on the outer side of the inner cover. They include sky radiation, (plus) outside soil radiation transmitted through the outer cover, (plus) radiation from the outer cover, (minus) radiation emitted by the inner cover, and (plus) radiation emitted by the outside of the inner cover and then reflected from the inside of the outer cover. The terms in the second set of brackets are for the radiation from below the cover, $R^{\uparrow}$, and (minus) the radiation emitted by the inner cover.

The net thermal radiation on the vegetation, soil, and curtain heat exchanger can be written

$$R_{kn} = \epsilon_k[-R_k + \sum_j \epsilon_j R_j V_{jk} + R^{\downarrow} V_{ck}] \quad (14\text{–}59)$$

where

$$V_{jk} = F_{jk} + \sum_{\ell} F_{j\ell}\rho_{\ell}F_{\ell k}$$

$$\rho_c = \rho_{cii} + \tau_{Rci}\rho_{coi}\tau_{Rci}$$

$$k = v,\ g,\ e;\ j = v,\ g,\ e;\ \ell = c,\ v,\ g,\ e$$

In words, the net thermal radiation for the vegetation, soil, and curtain heat exchanger is equal to minus the radiation emitted by that object plus the radiation received directly from the soil, vegetation, and exchanger plus the radiation from these surfaces that is reflected from all the other surfaces plus the radiation coming down from above, $R^{\downarrow}$, that is received directly plus reflected from the other surfaces. Note that ρ_c is the reflectance of the inside of the inner cover, ρ_{cii}, plus the reflectance of the inside of the outer cover, ρ_{coi}, multiplied by the transmittance of the inner cover, τ_{Rci}, twice to account for two passes through the inner cover. The other reflectances, ρ_c, ρ_g, and ρ_e, are one minus the corresponding emittances (parameters 11, 12, and 13 in appendix E).

The radiation coming down from the level of the covers, $R^{\downarrow}$, is defined as

$$R^{\downarrow} = F_{ac}A_gR_{ao}\tau_{Rco}\tau_{Rci} + \epsilon_{coi}R_{co}\tau_{Rci} + \epsilon_{cii}R_{ci} \quad (14\text{–}60)$$

The radiation going up toward the covers is defined as

$$R^{\uparrow} = \sum_j \epsilon_j R_j V_{jc} + R^{\downarrow} V_{cc} \quad (14\text{–}61)$$

To facilitate the solving of equations 14–1 through 14–8, equations 14–51, 14–52, and 14–53 need to be linearized. The method used is described in more detail in Kimball (*1981*) and uses equations of the form

$$R = R^o + \delta_R(T - T^o) \tag{14-62}$$

where

$$\delta_R = 4A\sigma(T^o + 273.16)^3 \tag{14-63}$$

All the variables in equations 14–62 and 14–63 are given the subscript *co, ci, v, g,* or *e,* depending on which of the five surfaces is being considered. The R^o and T^o are "old" values of R and T computed in a previous iteration.

It is convenient to define a notation-shortening variable, Y_R, as

$$Y_R = R^o - \delta_R T^o \tag{14-64}$$

Using equation 14–64 in equations 14–60 and 14–61, it is also convenient to define

$$Y^{\downarrow} = F_{ac}A_gR_{ao}\tau_{Rco}\tau_{Rci} + \epsilon_{coi}Y_{Rco}\tau_{Rci} + \epsilon_{cii}Y_{Rci} \tag{14-65}$$

and

$$Y^{\uparrow} = \sum_j \epsilon_j Y_{Rj}V_{jc} + Y^{\downarrow}V_{cc} \tag{14-66}$$

Similarly, using equation 14–64 in equations 14–56, 14–58, and 14–59, it is also convenient to define

$$\begin{aligned} Y_{Rcon} = \; & \epsilon_{coo}[F_{ac}A_gR_{ao} + F_{goc}A_gR_{go} - Y_{co}] \\ & + \epsilon_{coi}[-Y_{Rco} + \epsilon_{cio}Y_{Rci} + \tau_{Rci}Y^{\uparrow} + \epsilon_{coi}\rho_{cio}Y_{Rco}] \end{aligned} \tag{14-67}$$

and

$$\begin{aligned} Y_{Rcin} = \; & \epsilon_{cio}[(F_{ac}A_gR_{ao} + F_{goc}A_gR_{go})\tau_{Rco} + \epsilon_{coi}Y_{Rco} \\ & - Y_{Rci} + \epsilon_{cio}\rho_{coi}Y_{Rci}] + \epsilon_{cii}[Y^{\uparrow} - Y_{Rci}] \end{aligned} \tag{14-68}$$

and

$$Y_{Rkn} = \epsilon_k[-Y_{Rk} + \sum_j \epsilon_j Y_{Rj}V_{jk} + Y^{\downarrow}V_{cr}] \tag{14-69}$$

Humidity equations

As will be shown below, consideration is given to the humidity ratios at various locations in the greenhouse. When the humidity ratio is for a saturated water surface, several equations are used. First, the saturation vapor pressure, p^* (kPa), is computed from the temperature of the surface using Tentens' equation (Murray *1967*, Kimball *1981*):

$$p^* = 0.61078\exp[17.2694T/(T + 237.30)] \tag{14-70}$$

Next, the saturation humidity ratio, W^*, is computed from p^* and the barometric pressure, P_{ao} (kPa) (ASHRAE *1972*, p. 99):

$$W^* = 0.62198p^*/(P_{ao} - p^*) \tag{14-71}$$

The slope of the saturation humidity ratio curve with temperature, $\delta_W{}^*$ $= dW^*/dT$ ((kg/kg)/°C), is computed from

$$\delta_W{}^* = W^* \left[1 + \frac{W^*}{0.62198} \right] \left[\frac{4{,}098.03}{(T + 237.30)^2} \right] \tag{14–72}$$

The latent heat of vaporization, λ(J/kg), which also appears in the latent heat flux equations, is computed from

$$\lambda = 2.501 \times 10^6 - 2{,}381 T \tag{14–73}$$

Equation 14–73 was fitted to the data in List (*1958,* p. 343).

The humid specific heat of air, c_a (J/kg•°C), is computed from

$$c_a = 1{,}005 + 1{,}859\ W \tag{14–74}$$

The nonlinear saturation humidity ratio appears in several equations presented below. To facilitate solving equations 14–1 through 14–8, the humidity ratios are linearized as described previously (Kimball *1981*). Briefly,

$$W = W^o + \delta_W (T - T^o) \tag{14–75}$$

where W^o and T^o are "old" values computed in a previous iteration. All the variables in equation 14–75 are given the subscript *co, ci, v, g,* or *e*, depending on which of the five surfaces is being considered. The slope, δ_W, is computed from equation 14–72 for wet surfaces or is set equal to zero for dry surfaces. It is convenient to define the following variable to shorten later notation.

$$Y_W = W^o - \delta_W T^o \tag{14–76}$$

Convection

All of the convective fluxes of sensible, C_H, and latent, C_E, energy are computed individually, as illustrated in figure 12 by using the equations

$$C_H = Ah(T - T_a) \tag{14–77}$$

and

$$C_E = A \lambda K (W - W_a) \tag{14–78}$$

where the subscript *co, ci, v, g,* or e is added to each symbol (except T_a and W_a) to denote a particular surface. The air temperature and humidity terms refer to the air in contact with the particular surface; so outside air and humidity ratios are used for the outer cover, and inside values are used for the other four surfaces. Because the convective process is usually sufficiently turbulent, the same mechanism is operable for both sensible and latent heat transfer; and the mass transfer coefficients, *K,* are computed from the heat transfer coefficients, *h,* as $K = h/c_a$ (ASHRAE *1972,* p. 72). The exceptions to calculating *K* from h/c_a are the vegetation and soil surfaces, as will be discussed.

The humidity ratio, W, of a surface depends on the temperature of that surface. If the surface temperature is below the dewpoint of the surrounding air, condensate will form in a film on the surface. It is assumed that the condensate will drain away and not accumulate significantly. If the temperatures of the outer and inner covers and the curtain heat exchanger are above the dewpoint, they are assumed to be dry. Mathematically these cases can be expressed as

$$W = W^* \text{ and } \delta_W = \delta_W^* \text{ if } W^* < W_a \tag{14–79}$$

$$W = W_a \text{ and } \delta_W = 0 \quad \text{ if } W^* \geq W_a \tag{14–80}$$

The vegetation and soil surfaces are assumed to always be saturated, but there are additional resistances to evaporation (but not for condensation), as will be discussed.

Numerous expressions have been used by many investigators to compute the outside heat transfer coefficient, h_o, from the outside wind velocity, u_{ao} (Kimball *1973*). For this model a linear expression is used:

$$h_o = b_1 + b_2 u_{ao} \tag{14–81}$$

where the coefficients, b_1 and b_2, are parameters which the user can alter from simulation to simulation to suit the conditions. Numerous expressions have also been used to compute the heat transfer coefficient from inside air to the inside cover, h_{ci}(W/m^2• °C), from the temperature difference between the bulk air and the surface, ΔT, (Kimball *1973*). In this case, $\Delta T = |T_{ai} - T_{ci}|$, and the form of the equation used in the model is

$$h_i = b_3 (\Delta T)^{b_4} \tag{14–82}$$

where the coefficients b_3 and b_4 are parameters. If cooler air underlies warmer air, the value of h_i from equation 14–82 is reduced by one-half.

Many greenhouses are also equipped with powered circulation fans (Walker and Duncan *1974*) which create inside air movement and a larger inside air transfer coefficient, h_p. To model the turning on and off of such fans, h_p is computed from

$$h_p = \gamma_p h_{p1} \tag{14–83}$$

where γ_p is a control variable input that ranges from 0 to 1 from a type 12 time function, or similar device, and h_{p1} is a user-supplied parameter that is equal to the maximum value of h_p attained when $\gamma_p = 1$. If the value of h_i from equation 14–82 for heat transfer between the greenhouse air and a particular surface is less than h_p, then h_p is used instead for the value of the inside heat transfer coefficient to that particular surface.

The mass transfer coefficient, K_v (kg/s•m^2), is more complicated for the vegetation than for the other surfaces because it is assumed that the water evaporates into the substomatal cavities and then must pass a stomatal resistance, r_v, and a series air resistance, r_{av}, before reaching the bulk greenhouse air. On the other hand, when

$W_v < W_{ai}$ and moisture is condensing on the leaf, only the air resistance must be overcome. Thus,

$$K_v = 1/(r_{av} + r_v) \text{ if } W_v \geq W_{ai} \tag{14–84}$$

$$K_v = 1/r_{av} \qquad \text{if } W_v < W_{ai}$$

The air resistance is obtained from the inside heat transfer coefficient.

$$r_{av} = c_{ai}/h_v \tag{14–85}$$

The crop stomatal resistance, r_v (m^2s/kg), is assumed to be a function of the intensity of solar radiation inside the greenhouse (Kimball *1973*).

$$r_v = b_8 + b_9/(S_o\tau_S + b_{10}) \tag{14–86}$$

where b_8, b_9, and b_{10} are parameters for a particular crop.

The mass transfer coefficient K_g ($kg/\bullet m^2$) is computed similarly to K_v. It is assumed that the water evaporates below the soil surface at a temperature T_g and then must pass a soil surface resistance, r_g, and a series air resistance, r_{ag}, before reaching the bulk greenhouse air. This model is admittedly less realistic for soil than vegetation; but in a greenhouse the soil and crop will generally be well watered, so r_g will effectively be zero.

Otherwise, benches will be in use, and the soil will be dry at some very high constant value of r_g. The user provides r_g as a parameter, and r_{ag} is computed from

$$r_{ag} = c_{ai}/h_g \tag{14–87}$$

Then K_g is obtained from

$$K_g = 1/(r_{ag} + r_g) \tag{14–88}$$

Sensible and latent heats from external devices

The total sensible energy and total latent energy added to the greenhouse air from external devices are the sums of the energies added from individual devices. The temperature, T_{xj}; mass flow rate, M_{xj}; and the humidity ratio, W_{xj}, of each jth device are inputs to subroutine CGH. Then, the total sensible and latent heats, respectively, are computed from

$$\sum_j X_{Hj} = \sum_j M_{xj} c_{xj} (T_{xj} - T_{ai}) \tag{14–89}$$

$$\sum_j X_{Ej} = \sum_j M_{xj} \lambda_i (W_{xj} - W_{ai}) \tag{14–90}$$

The heat capacity of each separate air stream is computed individually from

$$c_{xj} = 1{,}005 + 1{,}859(W_{ai}{}^o + W_{xj})/2 \tag{14–91}$$

The sensible heat added to the cover or roof from an external device is computed from

$$X_c = M_{xc}c_{xc}[2(T_{xc} - T_{ci})] \tag{14–92}$$

where T_{xc} is the temperature of the fluid entering the cover from the external device. The temperature difference, $T_{xc} - T_{ci}$ is multiplied by 2 because it is assumed that the fluid in the roof is not well mixed and that T_{ci} is an average cover temperature halfway across the cover.

Similarly, the sensible heat added to the curtain heat exchanger from an external device is computed:

$$X_e = M_{xe}c_{xe}[2(T_{xe} - T_e)] \tag{14–93}$$

where T_{xe} is the fluid temperature entering the exchanger. The temperature difference, $T_{xe} - T_e$, is multiplied by 2 because it is assumed that the fluid in the exchanger is not well mixed and that T_e is an average temperature approximately halfway down the curtain.

Also, sensible heat may be similarly added to a storage layer in the soil, as described by

$$X_g = M_{xg}c_{xg}[2(T_{xg} - T_{gs})] \tag{14–94}$$

Like the temperature for the cover, the temperature T_{gs} is assumed to be an average halfway across the greenhouse, so the temperature change is multiplied by 2. Equation 14–94 omits any details about the heat transfer between the fluid and the soil. It can be expected to be a good model for a fluid in intimate contact with the soil layer, as, for example, the contact between the water and gravel in the Rutgers greenhouse (Mears et al. *1977*); but for fast-moving air in tubes (Dale et al. *1979*), heat transfer may be slow enough that a more detailed model is required. Also, latent heat transfer is not included.

A new device for heating greenhouses which has potential for conserving energy is an infrared radiant heating system (Rotz and Heins *1982*). Basically, the device consists of a burner and a long thin pipe(s) for mechanically conducting the exhaust gases to the outside. The pipe(s) runs the length of the greenhouse over the crop. A reflector is mounted above to reflect upward going radiation down toward the crop. The device conserves energy because the exhaust gases are cooler than those from a conventional burner and also because the air next to the greenhouse cover is cooler for the same vegetation temperature.

The infrared heater is modeled by specifying a maximum rated output capacity, X_{RM} (W), as a parameter, and multiplying it by an input control variable, γ_R:

$$X_R = \gamma_R X_{RM} \tag{14–95}$$

Most of the energy emitted by the heater impinges on the vegetation and soil below (assuming that any greenhouse having an infrared heater would not have curtain heat exchangers at the same time). The fraction, *f*, of the energy that is radiant must be specified by the user as another parameter. The remainder, $1 - f$ heats the

greenhouse air. It is assumed that the radiant energy from the infrared heater, like solar radiation, is apportioned between vegetation and soil according to their respective areas (equation 14–11). Then, the portions of the radiant energy from the infrared heater absorbed by the vegetation, soil, and air are computed from

$$X_{Rv} = X_R f A_{vs} / A_g \tag{14–96}$$

$$X_{Rg} = X_R f (A_g - A_{vs}) / A_g \tag{14–97}$$

$$X_{Ra} = X_R (1 - f) \tag{14–98}$$

Natural ventilation

Natural ventilation through ridge, side, or other ventilators is computed from

$$N_H = h_N (T_{ai} - T_{ao}) \tag{14–99}$$

$$N_E = \lambda_i K_N (W_{ai} - W_{ao}) \tag{14–100}$$

As usual, the mass transfer coefficient is computed from the heat transfer coefficient using the Lewis relation (ASHRAE *1972*, p. 72)

$$K_N = h_N / c_{ao} \tag{14–101}$$

To obtain h_N (W/°C), the rate of air change of the greenhouse is first computed from

$$u_N = (b_5 u_{ao} + b_6 \sqrt{T_{ai} - T_{ao}} + b_7) \gamma_N \tag{14–102}$$

u_N is the number of volumes of greenhouse air exchanged per hour. Experimental measurements of b_5, b_6, and b_7 are scarce. Okada and Takakura (*1973*) and Whittle and Lawrence (*1960*) have provided about the only available data.

The γ_N in equation 14–102 is a control variable input that can come from a type 4 thermostat or similar device. As it varies from 0 to 1, it controls the opening and closing of the ventilators.

After u_N is computed, h_N is obtained from

$$h_N = u_N v_{ai} D_{ao} c_{ao} / 3{,}600 \tag{14–103}$$

where the air density, D_{ao}, is computed from the outside temperature and pressure:

$$D_{ao} = P_{ao} / (0.287 (T_{ao} + 273.16)) \tag{14–104}$$

By proper choice of b_5 and b_7 with $b_6 = 0$ and $\gamma_N = 1$, a complete removal of the greenhouse cover can also be simulated. For example, if

$$b_5 = \frac{3{,}600 b_2 A_c}{v_{ai} D_{ao} c_{ao}} \tag{14–105}$$

and

$$b_7 = \frac{3{,}600 b_1 A_c}{v_{ai} D_{ao} c_{ao}} \qquad (14\text{–}106)$$

then equation 14–103 reduces to equation 14–81 and $h_N = h_o A_c$. The user should use typical values of air density, D_{ao}, and heat capacity, c_{ao}, when using equations 14–105 and 14–106 to calculate the parameter values for b_5 and b_7 for this no-cover case. Also, the inside heat transfer coefficient must be made very large. This can be accomplished by setting h_{p1} equal to 10,000 (see equation 14–83). To set the inputs γ_p and γ_N equal to 1.0, they can be connected to a device whose output is always 1, such as a type 13 reservoir with a parameter equal to 1. Of couse, for a no-cover case the cover must also be transparent to solar and thermal radiation, so τ_{Sco}, τ_{Sci}, τ_{Rco}, τ_{Rci} must be 1.0.

Infiltration

The infiltration of sensible energy and latent energy, respectively, by movement of air through cracks and intersticies is computed from

$$I_H = A_c h_I (T_{ai} - T_{ao}) \qquad (14\text{–}107)$$

$$I_E = A_c \lambda_i K_I (W_{ai} - W_{ao}) \qquad (14\text{–}108)$$

where h_I (W/m^2• °C) is the heat transfer coefficient for infiltration and K_I is the mass transfer coefficient for infiltration. From the Lewis relation (ASHRAE *1972*, p. 72),

$$K_I = h_I / c_{ao} \qquad (14\text{-}109)$$

The h_I is computed following Okada and Takakura (*1973*). First, a velocity of air movement, u_I, (mm/s or (m^3 of air × 10^3)/m^2 of cover/s) that is the average over the whole cover area is computed from

$$u_I = b_{11} u_{ao} + b_{12} \sqrt{T_{ai} - T_{ao}} + b_{13} \qquad (14\text{–}110)$$

Outside wind velocity and the temperature difference between the inside and outside air are assumed to affect natural ventilation and infiltration in a similar functional way. The primary difference is that natural ventilation is used to deliberately lower temperatures whereas infiltration is a consequence of the failure of greenhouse building materials to form a hermetic seal.

Few data are presently available about the coefficients in equation 14–110. However, it seems reasonable that they are a property of the cover and also might be affected by an inside circulation fan. Therefore, provision is made for changing the coefficients with γ_{ci} and γ_p. As shown in the codes in appendix E, the user must supply four values each for b_{11}, b_{12}, and b_{13}, the values corresponding to the following four cases: $\gamma_{ci} = \gamma_p = 0$; $\gamma_{ci} = 0$, $\gamma_p = 1$; $\gamma_{ci} = 1$, $\gamma_p = 0$; and $\gamma_{ci} = \gamma_p = 1$.

After u_I is computed, h_I is obtained from

$$h_I = u_I c_{ao} D_{ao} / 1{,}000 \qquad (14\text{–}111)$$

Soil heat flux

When this model was first constructed, the soil heat flux was computed by dividing the soil into layers and then computing the storage of heat in each layer from the difference between the fluxes entering and leaving each layer, as is done for the type 5 greenhouse. In some cases, especially unheated and uncooled greenhouses, the surface soil heat flux is very important. However, in order to simulate it accurately, thin surface layers were required; and then in order to satisfy stability criteria (see "Integration of Differential Equations"), time steps of 2 to 6 minutes were required. Such short time steps increased the required computation time by an order of magnitude in comparison to time steps of about an hour which usually can adequately follow diurnal weather patterns. Moreover, the iterations involved with solving the differential equations further increased the computational time by a factor of three or more.

Fortunately, a faster technique—variously called the transfer function method, the thermal response factor method, or conduction transfer function method—has been developed (Stephenson and Mitalas *1967,* Mitalas and Stephenson *1967,* Mitalas *1968,* Kusuda *1969*a,b, Peavy *1978,* Kimball *1983*). Peavy (*1978*) has published a computer program for computing the conduction transfer functions.

The conduction transfer function method is an analytical formulation that solves for temperatures or heat flows in multilayer slabs, based on past temperature history. Basically, the method utilizes the superposition principle in such a manner that the overall thermal response of a slab at a selected time is the sum of the responses caused by many individual temperature pulses during preceding times. Thus, by simulating the transient boundary temperatures using a train of pulses and then summing the heat fluxes caused by each pulse, the total heat flux at a given time can be derived. This derivation for the total heat flux is based on a solution of the basic differential equation for heat conduction obtained using a matrix of LaPlace transforms. Thus, the conduction transfer function method is conceptually and computationally more complex than the old, finite-difference numerical method, but the savings in computation time makes its use worthwhile.

To use the conduction transfer function method, one must have a set of coefficients specific for the thermal properties (conductivity, heat capacity) of the slab or floor being simulated. Obtaining these coefficients requires complicated computations (Kusuda *1969*a,b; Peavy *1978*); and, in effect, these prerun computations are substituted for run-time computations. However, once the coefficients are obtained, they can be used over and over again for slabs or floors with the same thermal properties. This requirement for constant thermal properties is a major limitation to many agricultural applications because changes in soil moisture conditions markedly alter thermal properties. However, most greenhouse growers maintain relatively constant soil moisture conditions with automatic irrigation systems, so the conduction transfer function method should be applicable for simulating soil heat flux in most greenhouses.

Conduction transfer functions have been presented for many combinations of building construction materials by ASHRAE (*1972* p. 425). Kusuda (*1979*a,b) and the ASHRAE Task Group on Energy Requirements for Heating and Cooling (*1975*) have presented conduction transfer functions for a few other building material combinations, including concrete over semi-infinite soil. Kimball (*1983*) has presented conduction transfer functions for a wide range of soil conditions and for the floor-heating system in the

Rutgers greenhouse (Mears et al. *1977*). The conduction transfer functions for a greenhouse sand culture system (Jensen and Hicks *1973,* Kimball and Mitchell *1979*) are presented in the solar greenhouse system example presented later.

In order to store heat from external devices such as solar collectors in a layer under the greenhouse, the soil under the greenhouse must be treated as though it were an upper slab over a lower semi-infinite region. The upper slab has temperatures T_g and T_{gs} at the surface and at the storage layer, respectively, and the corresponding soil heat fluxes are G_0 and G_{s0} (fig. 12). The lower semi-infinite region is at temperature T_{gs} at its top and at temperature T_d at some great depth. The value for T_d is a constant supplied by the user. The heat flux entering the top of the semi-infinite region is denoted G_{sd}. The upper slab can be composed of several layers of material with differing thermal properties, but the semi-infinite region must have constant thermal properties.

Following Peavy (*1978*), the soil heat flux at the soil surface is computed from

$$G_{0,t} = A_g B_{11} T_{g,t} - A_g B_{21} T_{gs,t} + \Sigma_0 \qquad (14\text{–}112)$$

where

$$\Sigma_0 = B_r G_{0,t-1} + A_g \sum_{m=2}^{M} [B_{1m} T_{g,t-m+1} - B_{2m} T_{gs,t-m+1}] \qquad (14\text{–}113)$$

The soil heat flux leaving the bottom of the upper slab is computed from

$$G_{s0,t} = A_g B_{21} T_{g,t} - A_g B_{31} T_{gs,t} + \Sigma_{s0} \qquad (14\text{–}114)$$

where

$$\Sigma_{s0} = B_r G_{s0,t-1} + A_g \sum_{m=2}^{M} [B_{2m} T_{g,t-m+1} - B_{3m} T_{gs,t-m+1}] \qquad (14\text{–}115)$$

The B_{1m}'s, B_{2m}'s, and B_{3m}'s in equations 14–112 to 14–115 are the conduction transfer functions, and the B_r is a common ratio between thermal response factors (Peavy *1978*, Kimball *1983*). All of these B's must be supplied by the user. They can be obtained from the references mentioned previously or from a prior run of Peavy's program. The slab of soil they represent should be at least about 10 cm thick in order to ensure that a minimum of about 25 total B's plus past temperatures are used for the soil heat flux prediction (Kimball *1983*).

The soil heat flux entering the top of the homogenous semi-infinite region can be obtained using thermal response factors. These thermal response factors can be calculated from the following set of simple equations (Kusuda *1969*a,b; Kimball *1983*):

$$B_{41} = 2\sqrt{(\kappa_g c_g D_g)/(\pi \Delta t)}$$

$$B_{4m} = B_{41}(\sqrt{m} - 2\sqrt{m-1} + \sqrt{m-2}) \quad m \geq 2 \qquad (14\text{–}116)$$

where κ_g, c_g, and D_g are the thermal conductivity (W/m·°C), heat capacity (J/kg·°C), and density (kg/m^3), respectively, of the soil comprising the semi-infinite region, and Δt is size of the simulation time step (s). The user must supply a value for B_{41}, and then the program computes the other B_{4m}'s. Kimball (*1983*) has presented values of

B_{41} for several cases. The maximum m used is the same as that given for the upper slab because using more terms for the lower, semi-infinite region than for the upper slab provides no additional accuracy so long as the total number of B's plus past temperatures is greater than about 25 (Kimball *1983*).

The soil heat flux entering the top of the semi-infinite region is computed from

$$G_{sd} = A_g B_{41}(T_{gs,t} - T_d) + \Sigma_{sd} \tag{14–117}$$

where

$$\Sigma_{sd} = A_g \sum_{m=2}^{M} B_{4m}(T_{gs,t-m+1} - T_d)$$

Thus, the soil heat fluxes are computed from the temperature extending M time steps back and from the soil heat fluxes of the previous time step. All the response factors and the past temperatures are stored and updated by the program at each time step. However, when first starting a simulation the user must supply estimates of the past temperatures and soil heat fluxes. Also, the conduction transfer functions for the upper slab and B_{41} for the semi-infinite region must be supplied. The conduction transfer functions and past temperatures could have been handled as ordinary parameters, as in all the other MEB subroutine models. However, because of the large number of values (25 or more), it seemed more convenient to use a standard table of values stored in COMMON. The user can fill in the form for complicated greenhouses, as provided in appendix D. The B's and M's are the outputs from prior runs obtained with Peavy's program, whereas the T's and G's are user estimates of the temperatures and heat fluxes for times prior to the initial run time. To improve these initial estimates, the user can run the first day's simulation a few times, and then use these computed temperatures and soil heat fluxes for the actual run.

Solving for T_{co}, T_{ci}, T_v, T_g, T_e, T_{ai}, W_{ai}, and T_{gs}

When all the defining energy flow equations are substituted into equations 14–1 through 14–8 and rearranged, the following equations result:

For the outer cover

$$\begin{aligned}
&T_{co}[-\delta_{Rco}\epsilon_{coo} + \delta_{Rco}\epsilon_{coi}(-1 + \epsilon_{coi}\tau_{Rci}^2 V_{cc} + \rho_{cio}) - A_c U_c - A_c h_o - A_c \lambda_o K_o \delta_{Wco}] \\
&+ T_{ci}[\delta_{Rci}\epsilon_{coi}(\epsilon_{cio} + \tau_{Rci}\epsilon_{cii} V_{cc}) + A_c U_c] \\
&+ T_v[\delta_{Rv}\epsilon_v \epsilon_{coi}\tau_{Rci} V_{vc}] \\
&+ T_g[\delta_{Rg}\epsilon_g \epsilon_{coi}\tau_{Rci} V_{gc}] \\
&+ T_e[\delta_{Re}\epsilon_c \epsilon_{coi}\tau_{Rci} V_{ec}] \\
&= -S_{co} - Y_{con} - A_c h_o T_{ao} + A_c \lambda_o K_o Y_{Wco} - A_c \lambda_o K_o W_{ao}
\end{aligned} \tag{14–118}$$

For the inner cover

$$
\begin{aligned}
&T_{co}[\delta_{Rco}\epsilon_{coi}(\epsilon_{cio}+\epsilon_{cii}\tau_{Rci}V_{cc})+A_cU_c]\\
&+T_{ci}\ [\delta_{Rci}\epsilon_{coi}(-1+\epsilon_{cio}\rho_{coi})+\delta_{Rci}\epsilon_{cii}(-1+\epsilon_{cii}V_{cc})\\
&\qquad -A_cU_c-A_ch_{ci}-A_c\lambda_iK_{ci}\delta_{Wci}-2M_{xc}c_{xc}]\\
&+T_v[\delta_{Rv}\epsilon_v\epsilon_{cii}V_{vc}]\\
&+T_g[\delta_{Rg}\epsilon_g\epsilon_{cii}V_{gc}]\\
&+T_e[\delta_{Re}\epsilon_e\epsilon_{cii}V_{ec}]\\
&+T_{ai}[A_ch_{ci}]\\
&+W_{ai}[A_c\lambda_iK_{ci}]\\
&=-S_{ci}-Y_{cin}+A_c\lambda_iK_{ci}Y_{Wci}-2M_{xc}c_{xc}T_{xc}
\end{aligned}
\tag{14–119}
$$

For the vegetation

$$
\begin{aligned}
&T_{co}[\delta_{Rco}\epsilon_{coi}\epsilon_v\tau_{Rci}V_{cv}]\\
&+T_{ci}[\delta_{Rci}\epsilon_{cii}\epsilon_vV_{cv}]\\
&+T_v[\delta_{Rv}\epsilon_v(-1+\epsilon_vV_{vv})-A_vh_v-A_v\lambda_iK_v\delta_{Wv}]\\
&+T_g[\delta_{Rg}\epsilon_g\epsilon_vV_{gv}]\\
&+T_e[\delta_{Re}\epsilon_e\epsilon_vV_{ev}]\\
&+T_{ai}[A_vh_v]\\
&+W_{ai}[A_v\lambda_iK_v]\\
&=-S_v-Y_{vn}+A_v\lambda_iK_vY_{Wv}-X_{Rv}
\end{aligned}
\tag{14–120}
$$

For the soil

$$
\begin{aligned}
&T_{co}[\delta_{Rco}\epsilon_{coi}\epsilon_g\tau_{Rci}V_{cg}]\\
&+T_{ci}[\delta_{Rci}\epsilon_{cii}\epsilon_gV_{cg}]\\
&+T_v[\delta_{Rv}\epsilon_v\epsilon_gV_{vg}]\\
&+T_g[\delta_{Rg}\epsilon_g(-1+\epsilon_gV_{gg})-A_gh_g-A_g\lambda_iK_g\delta_{Wg}-A_gB_{11}]\\
&+T_e[\delta_{Re}\epsilon_e\epsilon_gV_{eg}]\\
&+T_{ai}[A_gh_g]\\
&+W_{ai}[A_g\lambda_iK_g]\\
&+T_{gs}[A_gB_{21}]\\
&=-S_g-Y_{gn}+A_g\lambda_iK_gY_{Wg}-X_{Rg}+\Sigma_0
\end{aligned}
\tag{14–121}
$$

For the curtain heat exchanger

$$
\begin{aligned}
&T_{co}[\delta_{Rco}\epsilon_{coi}\epsilon_e\tau_{Rci}V_{ce}]\\
&+T_{ci}[\delta_{Rci}\epsilon_{cii}\epsilon_eV_{ce}]\\
&+T_v[\delta_{Rv}\epsilon_v\epsilon_eV_{ve}]\\
&+T_g[\delta_{Rg}\epsilon_g\epsilon_eV_{ge}]\\
&+T_e[\delta_{Re}\epsilon_e(-1+\epsilon_eV_{ee})-A_eh_e-A_e\lambda_iK_e\delta_{We}-2M_{xe}c_{xe}]\\
&+T_{ai}[A_eh_e]\\
&+W_{ai}[A_e\lambda_iK_e]\\
&=-Y_{en}+A_e\lambda_iK_eY_{We}-2M_{xe}c_{xe}T_{xe}
\end{aligned}
\tag{14–122}
$$

For the greenhouse air energy balance

$$
\begin{aligned}
& T_{ci}(A_c h_{ci} + A_c \lambda_i K_{ci} \delta_{Wci}) \\
& + T_v(A_v h_v + A_v \lambda_i K_v \delta_{Wv}) \\
& + T_g(A_g h_g + A_g \lambda_i K_g \delta_{Wg}) \\
& + T_e(A_e h_e + A_e \lambda_i K_e \delta_{We}) \\
& + T_{ai}(-A_c h_{ci} - A_v h_v - A_g h_g - A_e h_e - A_c h_l - h_N - \sum_j M_{xj} c_{xj}) \\
& + W_{ai}(-A_c \lambda_i K_c - A_v \lambda_i K_v - A_g \lambda_i K_g - A_e \lambda_i K_e - A_c \lambda_i K_l - \lambda_i K_N - \sum_j M_{xj} \lambda_i) \\
& = -A_c \lambda_i K_{ci} Y_{Wci} - A_v \lambda_i K_v Y_{Wv} - A_g \lambda_i K_g Y_{Wg} - A_e \lambda_i K_e T_{We} - A_c h_l T_{ao} \\
& \quad - A_c \lambda_i K_l W_{ao} - h_N T_{ao} - \lambda_i K_N W_{ao} - \sum_j M_{xj} c_{xj} T_{xj} - \sum_j M_{xj} \lambda_i W_{xj} - X_{Ra}
\end{aligned}
\tag{14–123}
$$

For the greenhouse air moisture balance

$$
\begin{aligned}
& T_{ci}(A_c \lambda_i K_{ci} \delta_{Wci}) \\
& + T_v(A_v \lambda_i K_v \delta_{Wv}) \\
& + T_g(A_g \lambda_i K_g \delta_{Wg}) \\
& + T_e(A_e \lambda_i K_e \delta_{We}) \\
& + W_{ai}(-A_{ci} \lambda_i K_{ci} - A_v \lambda_i K_v - A_g \lambda_i K_g - A_e \lambda_i K_e - A_c \lambda_i K_l - \lambda_i K_N - \sum_j M_{xj} \lambda_i) \\
& = -A_{ci} \lambda_i K_{ci} Y_{Wci} - A_v \lambda_i K_v Y_{wv} - A_g \lambda_i K_g Y_{Wg} - A_e \lambda_i K_e Y_{We} \\
& \quad - A_c \lambda_i K_l W_{ao} - \lambda_i K_N W_{ao} - \sum_j M_{xj} \lambda_i W_{xj}
\end{aligned}
\tag{14–124}
$$

For the soil storage layer

$$
\begin{aligned}
& T_g[A_g B_{21}] \\
& + T_{gs}[-A_g B_{31} - A_g B_{41} - 2M_{xg} c_{xg}] \\
& = -\Sigma_{s0} + \Sigma_{sd} - 2M_{xg} c_{xg} T_{xg}
\end{aligned}
\tag{14–125}
$$

Equations 14–118 through 14–125 form a set of eight simultaneous equations with eight unknowns: T_{co}, T_{ci}, T_v, T_g, T_e, T_{ai}, W_{ai}, and T_{gs}.

The method chosen for solution is Crout's triangularization with back substitution (Froberg *1965*, p. 78–81) because of its high accuracy (Kimball *1976*). When a simulation run is first started, the "old" values of the unknowns are set to the corresponding initial values of the user-supplied outputs for the type 14 greenhouse. When subroutine CGH is called, new values are computed. Then, the old values are set to the new ones and stored in labeled COMMON until the next time CGH is called.

Type 15 Simple Greenhouse

The type 15 simple greenhouse is illustrated in figure 17. Each arrow represents a flux of energy, with the direction of the arrows taken as positive. Energy fluxes included in the analysis are solar, *S*; combined conduction and convection, *C*; external device, X_j; and ventilation, *V*. The model for the type 15 simple greenhouse is similar to the models of Walker (*1965*) and Garzoli and Blackwell (*1971, 1973*) in that only one energy balance is used and evapotranspiration is handled rather crudely. Many of the transfer coefficients for convection, conduction, infiltration, and thermal radiation are lumped into a single overall *U* factor. Considerable versatility is retained, however, because the *U* can be adjusted to account for such factors as pulling a thermal screen at night or for using a powered circulation fan. No storage of heat in the soil is included in the analysis; but in a commercial heated greenhouse, the contribution of soil heat is relatively small. A big advantage of the type 15 greenhouse over the type 5 and type 14 ones is that the equation for the greenhouse air temperature is solved directly without iteration, so speed is obtained along with simplicity.

The following notation will be used:

A	area (m^2)
B	see equation 15–12
C	convection (W)
D	density (kg/m^3)
J	number of external devices
M	mass flow rate (kg/s)
P	pressure (kPa) or parameter
S	solar radiation (W/m^2)
T	temperature (°C)
U	overall heat transfer coefficient ($W/m^2 \cdot °C$)
V	rate of energy removed by ventilation (W)
X	energy from external device (W)
b	coefficients
c	heat capacity at barometric pressure (J/kg·°C)
f	fraction of energy that is latent
u	velocity of air movement (m/s) or greenhouse volumes per hour
v	greenhouse volume (m^3)
γ	control variable
η	saturation efficiency of evaporative pads (%)
ρ	reflectance
τ	transmittance of cover

Subscripts are as follows:

max	maximum
N	for natural ventilation
S	for solar radiation
V	for ventilation
Vp	for powered ventilation
VN	for natural ventilation
ai	inside air
an	air entering greenhouse
ao	outside air
c	cover
g	soil or ground
i	inside
j	index for external device
o	outside
p	for powered air circulation
vg	average of vegetation and soil
wb	outside wet bulb
x	external device
λ	latent heat
0	intercept or control variable equals 0
1	refers to the first member of a series, such as a series of coefficients; or it refers to the value of the control variable. Higher numbers identify higher members of a series.

Energy balance equation

Referring to figure 17, a balance of energy for the greenhouse can be written

$$S_i + \sum_j X_j - C - V = 0 \qquad (15\text{–}1)$$

Solar radiation

The solar heat gain inside the greenhouse, S_i, is computed from

$$S_i = A_g S_o \tau_S (1 - \rho_{vg}) \qquad (15\text{–}2)$$

The transmittance of the greenhouse cover for solar radiation, τ_S, is made a variable cover property and is computed from

$$\tau_S = (1 - \gamma_c)\tau_{S0} + \gamma_c \tau_{S1} \qquad (15\text{–}3)$$

where γ_c (input 6) is a control variable that ranges from 0 to 1 and can be input from a type 4 thermostat, a type 12 time clock, or similar device. The τ_{S0} (parameter 13) is the transmittance of the cover when $\gamma_c = 0$ while the τ_{S1} (parameter 16) is the transmittance when $\gamma_c = 1$. The γ_c controls other cover properties also, as will be discussed, so covers whose properties change can be modeled. Such covers include thermal screens and movable shades.

Sensible and latent energy from external devices

The total sensible and latent energy added to the greenhouse air from external devices is the sum of the energies added from individual devices. The temperature, T_j and mass flow rate, M_j, of each jth device are inputs to subroutine SGH. Then the total energy added is computed from

$$\sum_j X_j = \sum_j M_{xj} c (T_{xj} - T_{ai}) \tag{15–4}$$

The heat capacity of humid air at constant pressure, c, is assumed constant at 1,020 J/kg·°C.

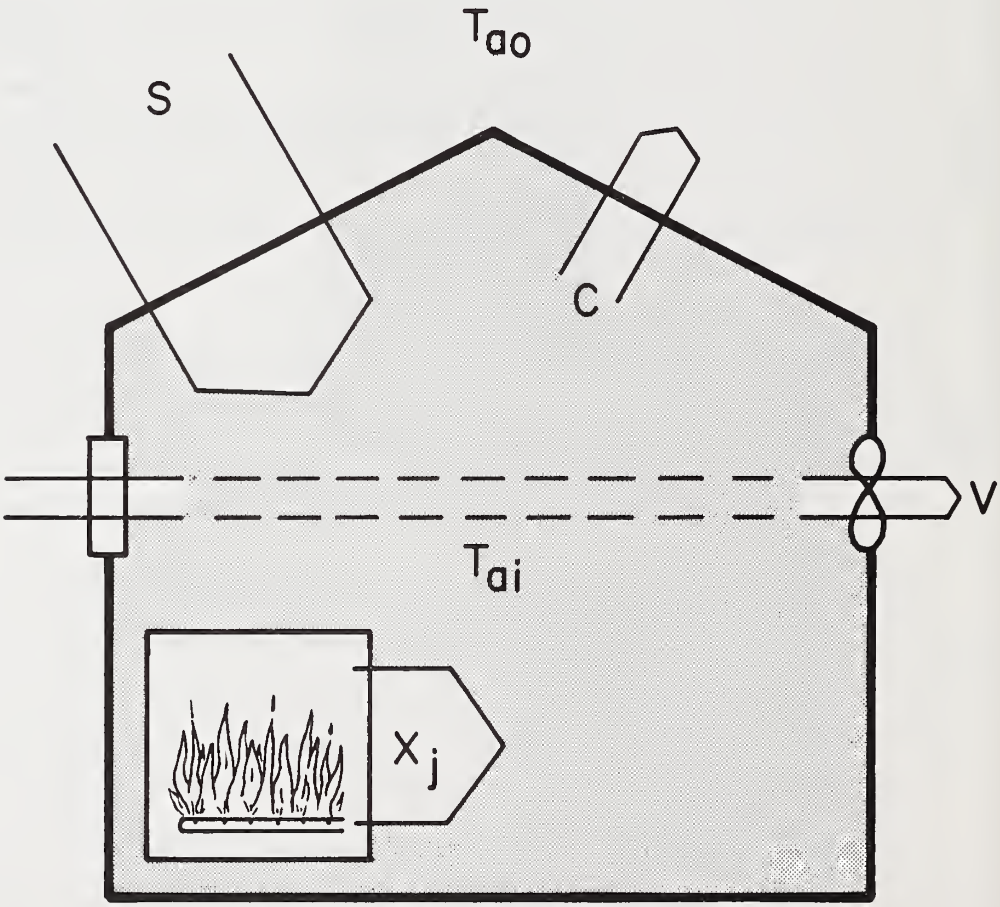

Figure 17.
Schematic illustration of a type 15 simple greenhouse showing the energy fluxes considered by the type 15 model.

Conduction and convection through the greenhouse cover

Conduction, C, through the greenhouse cover is computed from

$$C = A_c U (T_{ai} - T_{ao}) \tag{15–5}$$

The overall heat transfer coefficient, U (W/m^2·°C) is computed from

$$U = b_0 + b_1 u_{ao} \tag{15–6}$$

where u_{ao} (m/s) is the outside wind velocity. This U includes convection from the inside air to the cover, conduction through the greenhouse cover, and convection from the cover to the outside air. It also includes possible thermal radiation through partially transparent plastics, and infiltration of air through cracks and intersticies around glass panes or doors. By adjusting the coefficients in equation 15–6, the U factor for the greenhouse wall can be adjusted to account for varying conditions. In particular, the control variable γ_c (input 6) can be used to make needed changes in the cover properties, as, for example, when a thermal screen is drawn. To achieve this versatility, two values for b_0 and b_1 must be supplied as parameters, as indicated in appendix E, on the from in appendix D, and also as follows:

Item	$\gamma_c = 0$	$\gamma_c = 1$
τ_S	parameter 13	parameter 16
b_0	parameter 14	parameter 17
b_1	parameter 15	parameter 18

The values of the actual coefficients used in equation 15–6 are obtained by linear interpolations between the $\gamma = 0$ and the $\gamma_c = 1$ values, in a manner analogous to obtaining τ_S in equation 15–3.

Ventilation

The rate at which energy is removed from the greenhouse by forced or natural ventilation is computed from

$$V = \frac{v_{ai} u_V D_{ao} c (T_{ai} - T_{an})}{3{,}600\ (1 - f_\lambda)} \tag{15–7}$$

where u_V is the air exchange rate of the greenhouse in volumes per hour. It is computed for both natural, u_{VN}, and forced, u_{Vp}, ventilation; and then the larger of the two values is used in equation 15–7. Forced or powered ventilation, u_{Vp}, is computed as the product of maximum air changes per hour the fans can attain, u_{max} (parameter 10), times a control variable, γ_p (input 7), for turning the fans on or off:

$$u_{Vp} = u_{max} \gamma_p \tag{15–8}$$

Ranging from 0 to 1, γ_p can be supplied by a type 4 thermostat or similar device.

Natural ventilation u_{VN}, is computed from the oustide wind velocity:

$$u_{VN} = b_2 + b_3 u_{ao} \tag{15–9}$$

where u_{VN} has units of greenhouse volumes per hour and u_{ao} is the outside wind velocity in meters per second. A control variable, γ_N, is used to open and close the ventilators. Two sets of coefficients b_2 and b_3 must be supplied by the user as parameters, as indicated in appendix E and also as follows:

Item	$\gamma_N = 0$	$\gamma_N = 1$
b_2	parameter 6	parameter 8
b_3	parameter 7	parameter 9

When the vents are closed ($\gamma_N = 0$), the coefficients can be equal to zero, or, alternatively, they can be selected to model infiltration separately from the overall *U* factor for conduction and convection. The latter should be more realistic (Okada and Takakura *1973*) because conduction is more influenced by the materials of construction, whereas infiltration is more influenced by the quality of construction and the number and sizes of cracks and intersticies. Experimental measurements of b_2 and b_3 are scarce, with Okada and Takakura (*1973*) and Whittle and Lawrence (*1960*) providing about the only available data. Based on the data of Whittle and Lawrence, the program sets u_{VN} to a minimum value of 18/h when the vents are open wide ($\gamma_N = 1$), and the value from equation 15–9 is less than 18.

The air density D_{ao} is calculated from the barometric pressure (input 3) and the outside air temperature:

$$D_{ao} = P_{ao}/[0.287(T_{ao} + 273.16)] \tag{15–10}$$

The temperature at which the air enters the greenhouse, T_{an}, is computed from

$$T_{an} = T_{ao} - \eta(T_{ao} - T_{wb})/100 \tag{15–11}$$

where η (parameter 11) is the efficiency of evaporative cooler pads at the entrance to the greenhouse. If no evaporative pads are used, η can simply be set equal to zero, and the entering air temperature is the outside dry bulb temperature, T_{ao}. However, by setting η to 77 percent or some other typical value, a built-in evaporative cooler is modeled that is particularly appropriate for use with forced ventilation.

Equation 15–7 contains the term f_λ, the latent-heat fraction of the total energy removed by ventilation. As the air passes through the greenhouse and absorbs sensible heat, the air temperature increases. However, if there is moist soil or a transpiring crop in the greenhouse, some of the energy in the greenhouse will increase the moisture content of the greenhouse air by the latent heat of evaporation without raising the temperature. Garzoli and Blackwell (*1971*, *1973*), Lake et al. (*1966*), Morris (*1962*), and Morris et al. (*1957*) have all found values of f_λ close to 0.5 for freely transpiring, well-watered crops. By calculating backward from the greenhouse cooling system design standards (National Greenhouse Manufacturer's Association *1978*)

which gives the value of 0.04 m^3/s of air flow per cubic meter of greenhouse for a 4°C rise in air temperature, the standards can be shown to be based on an f_λ of approximately 0.5. While this approach of using a constant proportionality between sensible and latent energy does not account for variations in the physiological resistances to water loss of crops, it nevertheless has industry acceptance (Augsburger et al. *1970*) and some experimental verification.

Solution of the energy balance equation

When equations 15–4, 15–5, and 15–7 are substituted into equation 15–1 and rearranged, the following explicit equation is obtained for the inside air temperatue, T_{ai}:

$$T_{ai} = \frac{S_i + c\sum_j M_{xj}T_{xj} + A_cUT_{ao} + BT_{an}}{c\sum_j M_{xj} + A_cU + B} \tag{15–12}$$

where

$$B = \frac{v_{ai}u_V D_{ao} c}{3{,}600(1 - f_\lambda)}$$

After T_{ai} is computed, it is substituted into equations 15–4, 15–5, and 15–7. Then S_i, ΣX_j, C, the amount of sensible heat removed by ventilation, and V are all computed and returned to the main program as outputs listed in appendix E.

Type 16 Heater

The type 16 heater is one of the simplest of the device models. This air heater or furnace is modeled by specifying the maximum rate of sensible energy output, H_{max} (W), the heater is capable of delivering in parameter 1, and the maximum rate of water vapor production, E_{max} (kg/s), as parameter 3. The temperature of the air coming out of the heater, T_{a2} (output 1), is, computed from

$$T_{a2} = T_{a1} + \frac{\gamma H_{max}}{F_{max}(1{,}005 + 1{,}859W_{a1})}$$

where T_{a1} = temperature of air entering (°C)
γ = control variable. Varies from 0 to 1 and can be supplied by a type 4 thermostat or similar device.
F_{max} = maximum flow rate of internal fan of heater (kg/s)
W_{a1} = entering humidity ratio (kg/kg)

The humidity ratio of the air coming out of the heater, W_{a2} (output 3), is computed from

$$W_{a2} = W_{a1} + \frac{\gamma E_{max}}{F_{max}}$$

The mass flow rate of the air coming out the heater is output 2. It is set equal to F_{max} until γ is less than 1×10^{-10}, and then it is set equal to zero. This allows T_{a2} and W_{a2} and thus the heater output to vary proportionally with γ.

Many real heaters are not of the forced convection type and do not have an internal fan. The type 16 model can still be used, however, by simply choosing some reasonable mass flow rate for parameter 2 and pretending the heater is of the forced convection type. This works because the other component models that are likely to be used with the type 16 heater expect temperature, mass flow rate, and humidity ratio as the fluid stream information. Even if the specified flow rate is wrong, the type 16 model will compute a temperature that corresponds to the correct heater output (watts), and the other component models will decode and obtain this same output from the temperature and flow rate they receive. Even for electric heaters which add no latent heat to the air, the input humidity ratio (input 3) must still be connected to the humidity ratio of the space being heated. If input 3 were inadvertently connected to zero, for example, it would appear as if dry air were entering the space, and an error in the form of a false loss of latent energy would occur.

Type 17
Night-Sky Radiator

A section of a type 17 night-sky radiator is illustrated in figure 18. It consists of a thin surface of some high emittance material in contact with a stream of water for a heat transfer fluid. A cover of another material highly transparent to thermal radiation is stretched over the top to provide an insulating air layer. The device radiates energy to the night sky from the water, and the water cools as it flows from one side of the section to the other. Because of the insulating air layer, radiation can cool the water to below the ambient air temperature. When the water is warmer than air temperature, however, greater cooling can be achieved by removing the insulating air layer to facilitate additional heat loss by convection.

The emittance and transmittance of the atmosphere are not uniform with wavelength (Idso *1981*). The region between 8 and 14 μm is generally quite transparent and is known as the atmospheric window. Outside the window, from 0 to 8 μm and from 14

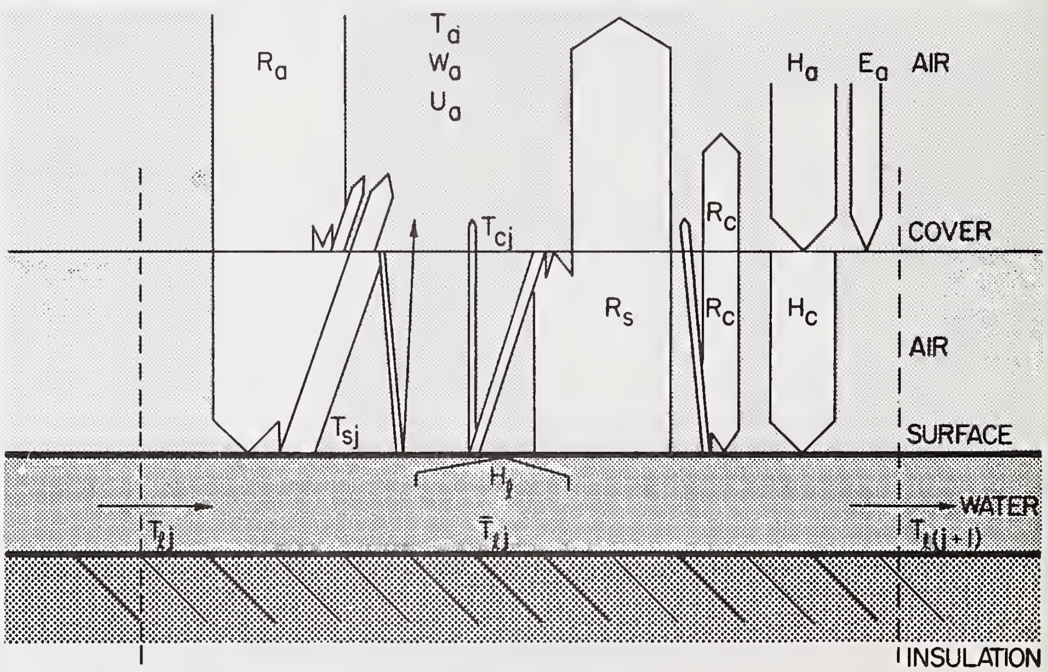

Figure 18.
Schematic illustration of the j^{th} section of a type 17 night-sky radiator showing the energy fluxes considered by the type 17 model.

to ∞ μm, the atmosphere is essentially opaque. Catalanotti et al. (*1975*) have shown that it is advantageous for a night-sky radiator to have a selective surface. An ideal surface for obtaining temperatures below air temperature would be to have an emittance of 1.0 in the atmospheric window wave band and an emittance of 0.0 outside the wave band. The reason for the zero emittance outside the window is that the surface then has a reflectance of 1.0 and will reflect all downcoming sky radiation. To accommodate selective surfaces and the selective atmosphere, the type 17 night-sky radiator handles window radiations separately from outside window radiations. The emittances, reflectances, and so forth, for the window (subscript *w*) and outside window (subscript *o*) radiations used are average values because generally neither real surfaces nor the atmosphere are spectrally flat either within the window or outside of it.

As will be discussed in greater detail, the type 17 night-sky radiator has three modes of operation. The first mode is the one illustrated in figure 18, with a nearly transparent cover and an insulating air layer.

A second mode of operation is for no cover and no insulating air layer. When the user specifies mode = 2 (parameter 14), subroutine NSRAD ignores parameters 8, 9, 10, and 11, which are the cover transmittances and reflectances. Instead, it sets the cover transmittance equal to zero and the cover reflectance equal to 1 minus the surface emittance (parameters 11 and 12). It also sets the inside convective heat transfer coefficient effectively to infinity so that the computed temperature difference between the surface and a now imaginary cover is zero.

A third mode of operation is to flood the area with water to obtain additional cooling from evaporation. When the user specifies mode = 3, subroutine NSRAD will set up the cover transmittance to 0.0 and the cover reflectance to 0.04, the values for water. In this mode also it sets the inside convective heat transfer effectively to infinity so that the "cover" and surface temperatures will be the same. In this mode the surface is a water surface. For modes 1 and 2, subroutine NSRAD checks for the dew deposition on the cover. If the temperature of the cover decreases below the dewpoint, the subroutine then uses water values for the thermal radiation properties. These are transmittance = 0, reflectance = 0.04, and emittance = 0.96.

The following notations will be used:

A	area (m^2)
D	density (kg/m^3)
E	rate of latest heat transfer (W)
H	rate of sensible heat transfer (W)
J	total number of segments
K	mass transfer coefficient ($kg/s{\cdot}m^3$)
M	mass flow rate (kg/s)
P	barometric pressure (kPa)
Q	total rate of enthalpy change of the water (W)
R	thermal radiation (W, except W/m^2 for sky radiation per horizontal area)
S	solar radiation (W/m^2)
T	temperature (°C)
W	humidity ratio (kg/kg)
b	coefficient

c heat capacity (J/kg•°C)
f fraction of black body radiation emitted in particular wave band
h convective heat transfer coefficient (W/m^2•°C)
p vapor pressure (kPa)
α absorptance (= emittance)
β see equation 17–2
δ slope with respect to temperature (change/°C)
ϵ emittance (= absorptance)
λ latent heat of vaporization (J/kg)
ρ reflectance
σ Stephan-Boltzman constant (W/m^2•K^4)
τ transmittance
ψ see equation 17–3

Subscripts are as follows:

R for thermal radiation
S for solar radiation
W for humidity ratio
a air
ao air outside 8- to 14-μm window
aw air in 8- to 14-μm window
c cover
co cover outside 8- to 14-μm window
cw cover in 8- to 14-μm window
i inside or between cover and surface
j index for segments of radiator
ℓ liquid (water)
n net (downcoming minus upgoing)
o outside 8- to 14-μm band when referring to radiation or outside air when referring to convection
s surface
so surface outside 8- to 14-μm window
sw surface inside 8- to 14-μm window
w within 8- to 14-μm atmospheric window
0 refers to coefficient number 1
1 refers to coefficient number 2;
series of numbers and coefficients continues

Superscripts are as follows:

* saturated condition
old from previous iteration
$\bar{}$ average

Energy balance equations

A type 17 night-sky radiator is shown in figure 18. Water is flowing into the section at a temperature $T_{\ell j}$ and cools to a temperature $T_{\ell(j+1)}$ at the end of the jth section. Each arrow represents a flux of energy, with the direction of the arrows taken as

positive. Multiple reflections of the radiation fluxes give rise to infinite geometric series of terms involving the product of the reflectance of the cover, ρ_c, and the reflectance of the surface, ρ_s, as shown on the left-hand side of equation 17–1. The series can be written in the more convenient closed form on the right-hand side (Jolley *1961*, p. 2).

$$1+\rho_s\rho_c+(\rho_s\rho_c)^2+(\rho_s\rho_c)^3+(\rho_s\rho_c)^4+\ldots=\frac{1}{1-\rho_s\rho_c} \qquad (17\text{–}1)$$

Thus, wherever the factor $1/(1-\rho_s\rho_c)$ appears in the following equations, the reader should remember that the whole series of multiple reflections is being evaluated.

Referring to figure 18 and using equation 17–1, an energy balance on the *j*th section of the surface can be written as

$$R_{aw}\beta_{aw}A_j+R_{ao}\beta_{ao}A_j+R_{swj}\beta_{sw}+R_{soj}\beta_{so}$$

$$+R_{cwj}\beta_{cw}+R_{coj}\beta_{co}+H_{cj}+H_{\ell j}+S_j=0 \qquad (17\text{–}2)$$

where

$$\beta_{aw}=\frac{\tau_{cw}\alpha_{sw}}{1-\rho_{sw}\rho_{cw}}, \qquad \beta_{ao}=\frac{\tau_{co}\alpha_{so}}{1-\rho_{so}\rho_{co}}$$

$$\beta_{sw}=\frac{\rho_{cw}\alpha_{sw}}{1-\rho_{sw}\rho_{cw}}-1, \qquad \beta_{so}=\frac{\rho_{co}\alpha_{so}}{1-\rho_{so}\rho_{co}}-1$$

$$\beta_{cw}=\frac{\alpha_{sw}}{1-\rho_{sw}\rho_{cw}}, \qquad \beta_{co}=\frac{\alpha_{so}}{1-\rho_{so}\rho_{co}}$$

Similarly, an energy balance on the *j*th section of the cover can be written as

$$R_{aw}\psi_{aw}A_j+R_{ao}\psi_{ao}A_j+R_{swj}\psi_{sw}+R_{soj}\psi_{so}$$

$$+R_{cwj}\psi_{cw}+R_{coj}\psi_{co}+H_{aj}+E_{aj}-H_{cj}=0 \qquad (17\text{–}3)$$

where

$$\psi_{aw}=\alpha_{cw}+\frac{\alpha_{cw}\tau_{cw}\rho_{sw}}{1-\rho_{sw}\rho_{cw}}, \qquad \psi_{ao}=\alpha_{co}\frac{\alpha_{co}\tau_{co}\rho_{so}}{1-\rho_{so}\rho_{co}}$$

$$\psi_{sw}=\frac{\alpha_{cw}}{1-\rho_{sw}\rho_{cw}}, \qquad \psi_{so}=\frac{\alpha_{co}}{1-\rho_{so}\rho_{co}}$$

$$\psi_{cw}=\frac{\rho_{sw}\alpha_{cw}}{1-\rho_{sw}\rho_{cw}}-2, \qquad \psi_{co}=\frac{\rho_{so}\alpha_{co}}{1-\rho_{so}\rho_{co}}-2$$

Thermal radiation

The total sky radiation per unit area, R_a (W/m^2), and the sky radiation within the 8- to 14-μm atmospheric window per unit area, R_{aw} (W/m^2), are inputs 3 and 4. They can be obtained as outputs 21 and 22 from the type 1 reader. As mentioned previously, the reader reads the output from a DECODER program which computes R_a and R_{aw} from National Weather Service temperature, vapor pressure, and cloud cover data using the model of Kimball et al. (*1982*). Then, the sky radiation outside the window, R_{ao}, is computed from

$$R_{ao} = R_a - R_{aw} \tag{17–4}$$

The radiation emitted from the jth section of the surface within the 8- to 14-μm band, R_{sw} (W), is computed from

$$R_{swj} = \epsilon_{sw} A_j f_{swj} \sigma (T_{sj} + 273.16)^4 \tag{17–5}$$

where f_{swj}, 8- to 14-μm fraction of total black body radiation emitted at temperature T_{sj}, is computed from

$$f_{swj} = 0.34906 + 1.2495 \times 10^{-3} T_{sj} - 0.91397 \times 10^{-5} T_{sj}^2 \tag{17–6}$$

Equation 17–6 was obtained by fitting ($R^2 = 0.99990$) a quadratic to values calculated from table 2 of Harrison (*1960*, p. 156) from -90°C to $+70$°C. To facilitate later solution of equations 17–2 and 17–3, equation 17–5 is linearized using (Kimball *1981*)

$$R_{swj} = R_{swj}^{old} + \delta_{Rswj} (T_{sj} - T_{sj}^{old}) \tag{17–7}$$

where

$$\delta_{Rswj} = 4 \epsilon_{sw} A_j f_{swj}^{old} \sigma (T_{sj}^{old} + 273.16)^3 \tag{17–8}$$

The "old" superscript means an estimate from the previous iteration.

The radiation emitted from the jth section of the surface outside of the 8- to 14-μm band, R_{soj}, is computed from

$$R_{soj} = \epsilon_{so} A_j f_{soj} \sigma (T_{sj} + 273.16)^4 \tag{17–9}$$

where f_{soj}, the fraction of black body radiation emitted outside of the 8- to 14-μm band at temperature T_{sj} is computed from

$$f_{soj} = 1 - f_{swj} \tag{17–10}$$

Equation 17–9 is linearized using

$$R_{soj} = R_{soj}^{old} + \delta_{Rsoj} (T_{sj} - T_{sj}^{old}) \tag{17–11}$$

where

$$\delta_{Rsoj} = 4 \epsilon_{so} A_j f_{soj}^{old} \sigma (T_{sj}^{old} + 273.16)^3 \tag{17–12}$$

Likewise, the radiation emitted from the jth section of the cover is computed from

$$R_{cwj} = \epsilon_{cw} A_j f_{cwj} \sigma (T_{cj} + 273.16)^4 \tag{17–13}$$

$$R_{coj} = \epsilon_{co} A_j f_{coj} \sigma (T_{cj} + 273.16)^4 \tag{17–14}$$

which are linearized using

$$R_{cwj} = R_{cwj}^{old} \delta_{Rcwj} (T_{cj} - T_{cj}^{old}) \tag{17–15}$$

where

$$\delta_{Rcwj} = 4\epsilon_{cw} A_j f_{cwj}^{old} (T_{cj}^{old} + 273.16)^3 \tag{17–16}$$

and

$$R_{coj} = R_{coj}^{old} + \delta_{Rcoj} (T_{cj} - T_{cj}^{old}) \tag{17–17}$$

where

$$\delta_{Rcoj} = 4\epsilon_{co} A_j f_{coj}^{old} \sigma (T_{cj}^{old} + 273.16)^3 \tag{17–18}$$

Convection above the cover

The rate at which sensible heat is convected from the air to the jth section of the cover is computed from

$$H_{aj} = A_j h_o (T_a - T_{cj}) \tag{17–19}$$

where

$$h_o = b_0 + b_1 u_a \tag{17–20}$$

The h_o (W/m^2·°C) is the outside heat transport coefficient, u_a (m/s, input 1) is the outside wind velocity, and b_0 and b_1 are coefficients. Numerous expressions have been used for h_o (Kimball *1973*). Duffie and Beckman (1974, p. 83) list $b_0 = 5.7$ and $b_1 = 3.8$ from McAdams.

The rate at which latent heat is convected from the air to the jth section of cover when the cover becomes sufficiently cold is

$$E_{aj} = A_j K_o \lambda (W_a - W_{cj}) \tag{17–21}$$

where the mass transfer coefficient, K_o, is computed from the heat transfer coefficient (ASHRAE *1972*, p. 72) and the specific heat capacity of the air, c_a:

$$K_o = h_o / c_a$$

$$c_a = 1{,}005 + 1{,}859 W_{ao} \tag{17–22}$$

The latent heat of vaporization, λ (J/kg), is computed from

$$\lambda = 2.501 \times 10^6 - 2{,}381 T_c^{old} \tag{17-23}$$

The cover humidity ratio, W_c, depends on the temperature of the cover. If the temperature of the cover is below the dewpoint of the outside air (modes 1 and 2), or the device is flooded (mode 3), the cover is at saturation. This can be expressed as

$$\begin{aligned} &W_{cj} = W_{cj}^* \text{ if } W_{cj}^* < W_a \text{ for mode } = 1 \text{ or } 2 \\ &W_{cj} = W_a \text{ if } W_{cj}^* \geq W_a \text{ for mode } = 1 \text{ or } 2 \\ &W_{cj} = W_{cj}^* \text{ for mode } = 3 \end{aligned} \tag{17-24}$$

The saturation humidity ratio is computed from

$$W_{cj}^* = 0.62198 p_{cj}^* / (P_a - p_{cj}^*) \tag{17-25}$$

where the saturation vapor pressure, p_{cj}^*, is computed from Tetens' equation (Murray *1967*):

$$P_{cj}^* = 0.61078 \exp[17.2694 T_{cj}^{old} / (T_{cj}^{old} + 237.30)] \tag{17-26}$$

The slope of the saturation humidity ratio curve with temperature, $\delta_{Wcj}^* = dW_{cj}^*/dT$, is computed from (Kimball *1981*):

$$\delta_{Wcj}^* = W_{cj}^* \left(1 + \frac{W_{cj}^*}{0.62198}\right)\left[\frac{4{,}098.03}{(T_{cj}^{old} + 237.30)^2}\right] \tag{17-27}$$

Thus, equation 17–24 is linearized using

$$W_{cj} = W_{cj}^{old} + \delta_{Wcj}(T_{cj} - T_{cj}^{old}) \tag{17-28}$$

where

$$\begin{aligned} &\delta_{Wcj} = \delta_{Wcj}^* \text{ if } W_{cj}^{old} < W_a \text{ for mode } = 1 \text{ or } 2 \\ &\delta_{Wcj} = 0 \text{ if } W_{cj}^{old} \geq W_a \text{ for mode } = 1 \text{ or } 2 \\ &\delta_{Wcj} = \delta_{Wcj}^* \text{ for mode } = 3 \end{aligned} \tag{17-29}$$

Convection below the cover

The rate at which sensible heat is convected and conducted downward from the cover to the surface is computed from

$$H_{cj} = A_j h_{ij} (T_{cj} - T_{sj}) \tag{17-30}$$

where h_{ij} (W/m$^2\cdot$°C) is the inside heat transfer coefficient. Numerous expressions have been used to compute inside heat transfer coefficients from temperature differences between bulk air and a surface (Kimball *1973*). The form of the equation used is

$$h_{ij} = b_2(\Delta T)^{b_3} \tag{17–31}$$

where b_2 and b_3 are parameters 5 and 6, and ΔT is $T_{cj} - T_{sj}$ or $T_{sj} - T_{cj}$, whichever is positive.

ASHRAE (*1972*, p. 40) lists b_2 as 1.52 and b_3 as 0.33. Subroutine NSRAD divides the value from equation 17–31 by 2 because there are two film resistances, one for the cover annd the other for the radiating surface. Also following ASHRAE, the value from equation 17–31 is divided by 2 again when the temperature of the cover, T_{cj}, is warmer than that of the radiating surface, T_{sj}, which is the normal operating condition.

When mode = 2 or 3, h_{ij} is set equal to 500 W/m$^2\cdot$°C to remove the insulating effect of an air layer.

It is assumed that there is no latent heat transfer below the cover because the air layer is too thin to contain a significant quantity of precipitable water.

Convection from the water to the surface

The rate at which sensible heat is convected and conducted from the water to the surface is computed from

$$H_{\ell j} = A_f h_{\ell j}(\overline{T}_{\ell j} - T_{sj}) \tag{17–32}$$

where $h_{\ell j}$ *(W/m$^2\cdot$* °C) is the liquid heat transfer coefficient. It is computed from

$$h_{\ell j} = b_4(\overline{T}_{\ell j} - T_{sj})^{0.33} \tag{17–33}$$

where b_4 is parameter 7. Equation 17–33 was obtained following Duffie and Beckman (*1974*, equation 4.11.8) for one water film (rather than two as in Dufie and Beckman) and a 5-cm depth of water. With natural convection as the predominant mechanism of heat transfer, b_4 is 230. The assumption is also made that the minimum value of $h_{\ell j}$ is 60 W/m$^2\cdot$°C, which corresponds to the thermal conductivity of water through a film 1 cm thick.

In equations 17–32 and 17–33 $\overline{T}_{\ell j}$ is the average bulk water temperature somewhat below the temperature of the radiating surface. For the *j*th section, it is defined as the average temperature between the water entering and leaving section *j*:

$$\overline{T}_{\ell j} = (T_{\ell j} + T_{\ell(j+1)})/2 \tag{17–34}$$

The rate at which heat is convected to the surface must equal the rate at which the water cools. For the segment of the radiator shown in figure 18,

$$H_{\ell j} = Fc_\ell(T_{\ell j} - T_{\ell(j+1)}) \tag{17–35}$$

Combining equations 17–32, 17–34, and 17–35,

$$\bar{T}_{\ell j}=\frac{2Fc_{\ell}T_{\ell j}+A_j h_{\ell j}T_{sj}^{\text{old}}}{2Fc_{\ell}+A_j h_{\ell j}} \qquad (17\text{–}36)$$

Equation 17–36 links the average water temperature of a segment to the temperature of the water entering the segment, $T_{\ell j}$, and the temperature of the radiating surface of the segment, T_{sj}. Starting with the first segment, the entering water temperature is obtained from input 1. The surface temperature, T_{sj}, is not known a priori but must come from the solution of the energy balance equations 17–2 and 17–3. Yet, to solve these equations, a value for $\bar{T}_{\ell j}$ is needed to obtain $H_{\ell j}$ from equation 17–32. Therefore $\bar{T}_{\ell j}$ is first estimated from equation 17–36 by using T_{sj}^{old} from the previous iteration for T_{sj}. As the iteration proceeds, progressively better estimates of T_{sj} lead to better estimates of $\bar{T}_{\ell j}$, which lead to better estimates of T_{sj}, and so on to convergence.

Solar radiation

It is anticipated that a night-sky radiator would usually be operated only at night when solar radiation is absent. However, there may be some possibility for using radiators that are shaded from the direct sun. In either event, there is a need to predict radiator temperatures during the daytime so that thermostats can be used for controllers. The solar radiation absorbed by the jth section of the surface is modeled simply as

$$S_j=(\tau\alpha)_S A_j S_a \qquad (17\text{–}37)$$

where $(\tau\alpha)_S$ is the effective transmittance-absorptance product of the cover and surface for solar radiation, and S_a is the solar radiation impinging on the radiator. Usually, S_a is the total direct beam plus diffuse radiation, but it is only the diffuse for shaded radiators. It is assumed that no significant amount of solar radiation is absorbed by the cover.

Solving for T_{sj} and T_{cj}

When equations 17–7, 17–11, 17–15, 17–17, 17–19, 17–21, 17–28, 17–30, 17–32, and 17–37, are substibuted into equations 17–2 and 17–3 and rearranged, the following equations result:

For the surface,

$$\begin{aligned}
&T_{sj}(\delta_{Rswj}\beta_{sw}+\delta_{Rsoj}\beta_{so}-A_j h_{ij}-A_j h_{\ell j})\\
&+T_{cj}(\delta_{Rcwj}\beta_{cw}+\delta_{Rcoj}\beta_{co}+A_j h_{ij})\\
&=-R_{aw}\beta_{aw}A_j-R_{ao}\beta_{ao}A_j-(R_{swj}^{\text{old}}-\delta_{Rswj}T_{sj}^{\text{old}})\beta_{sw}\\
&\quad-(R_{soj}^{\text{old}}-\delta_{Rsoj}T_{sj}^{\text{old}})\beta_{so}-(R_{cwj}^{\text{old}}-\delta_{Rcwj}T_{cj}^{\text{old}})\beta_{cw}\\
&\quad-(R_{coj}^{\text{old}}-\delta_{Rcoj}T_{cj}^{\text{old}})\beta_{co}-A_j h_{\ell j}\bar{T}_{\ell j}-S_j
\end{aligned} \qquad (17\text{–}38)$$

For the cover,

$$
\begin{aligned}
& T_{sj}(\delta_{Rswj}\psi_{sw} + \delta_{Rsoj}\psi_{so} + A_j h_{ij}) \\
& + T_{cj}(\delta_{Rcwj}\psi_{cw} + \delta_{Rcoj}\psi_{co} - A_j h_o - A_j K_o \lambda \delta_{Wcj} - A_j h_{ij}) \\
& = -R_{aw}\psi_{aw}A_j - R_{ao}\psi_{ao}A_j - (R_{swj}{}^{old} - \delta_{Rswj}T_{sj}{}^{old})\psi_{sw} \\
& \quad - (R_{soj}{}^{old} - \delta_{Rsoj}T_{sj}{}^{old})\psi_{so} - (R_{cwj}{}^{old} - \delta_{Rcwj}T_{cj}{}^{old})\psi_{cw} \\
& \quad - (R_{coj}{}^{old} - \delta_{Rcoj}T_{cj}{}^{old})\psi_{co} - A_j h_o T_a - A_j K_o \lambda W_a \\
& \quad + A_j K_o \lambda (W_{cj}{}^{old} - \delta_{Wcj}T_{cj}{}^{old})
\end{aligned}
\qquad (17\text{–}39)
$$

Equations 17–38 and 17–39 form a set of two equations with two unknowns, and they can be solved easily using Cramer's rule. Starting with the first section of the radiator, an initial guess is made for $T_{s1}{}^{old}$ and $T_{c1}{}^{old}$. Then, improved estimates of T_{s1} and T_{c1} are obtained from equations 17–38 and 17–39. The old values are set equal to these new ones and the iteration proceeds to convergence. Because the slopes for radiation, δ_R, and humidity ratio, δ_W, are obtained from analytical equations, the convergence is rapid and accurate.

After T_{c1} and T_{s1} are obtained from the first section, the average water temperature for the first section $\overline{T}_{\ell 1}$ (from equation 17–36), is used in equation 17–34 to obtain the temperature of the water leaving the first section, $T_{\ell 2}$. This exit temperature is then the entering water temperature for the second section, and the computations are repeated for the second section, then the third, and so forth, for all the sections. The number of sections has been arbitrarily set in subroutine NSRAD to 5. This should be adequate to describe the nonlinear change in temperature with distance down the radiator for most cases. It can be changed to another number by changing a single statement in NSRAD. If the user sets parameter 15 to 1, a segment-by-segment summary of the temperatures and energy fluxes along the radiator can be obtained.

Net long-wave radiation

Net long-wave radiation is defined as the rate of downcoming radiation minus that of the upgoing. The net exchanges of radiation above the cover, R_{nc}, and between the cover and surface, R_{ns}, are two entities that can be measured using net radiometers. The net radiation also is a direct measure of the effectiveness of the device as a radiator. Therefore, after T_{sj} and T_{cj} are computed for each section, subroutine NSRAD also computes R_{ncj} and R_{nsj} for each jth section. Referring to figure 18 and equation 17–1, the equations used are derived as follows:

Above the cover,

$$
\begin{aligned}
R_{ncj} = {} & R_{aw}\left(1 - \rho_{cw} - \frac{\rho_{sw}\tau_{cw}{}^2}{1-\rho_{sw}\rho_{cw}}\right) + R_{ao}\left(1 - \rho_{co} - \frac{\rho_{so}\tau_{co}{}^2}{1-\rho_{so}\rho_{co}}\right) \\
& - R_{swj}\left(\frac{\tau_{cw}}{1-\rho_{sw}\rho_{cw}}\right) - R_{soj}\left(\frac{\tau_{co}}{1-\rho_{so}\rho_{co}}\right) \\
& - R_{cwj}\left(1 + \frac{\rho_{sw}\tau_{cw}}{1-\rho_{sw}\rho_{cw}}\right) - R_{coj}\left(1 + \frac{\rho_{so}\tau_{co}}{1-\rho_{so}\rho_{co}}\right)
\end{aligned}
\qquad (17\text{–}40)
$$

Between the cover and surface,

$$R_{nsj} = R_{aw} \left(\frac{\tau_{cw} - \tau_{cw}\rho_{sw}}{1 - \rho_{sw}\rho_{cw}} \right) + R_{ao} \left(\frac{\tau_{co} - \tau_{co}\rho_{so}}{1 - \rho_{so}\rho_{co}} \right)$$

$$- R_{swj} \left(\frac{1 - \rho_{cw}}{1 - \rho_{sw}\rho_{cw}} \right) - R_{soj} \left(\frac{1 - \rho_{co}}{1 - \rho_{so}\rho_{co}} \right)$$

$$+ R_{cwj} \left(\frac{1 - \rho_{sw}}{1 - \rho_{sw}\rho_{cw}} \right) + R_{coj} \left(\frac{1 - \rho_{so}}{1 - \rho_{so}\rho_{co}} \right) \quad (17\text{–}41)$$

Outputs

The code for the outputs is listed in appendix E. Output 1 is the water temperature from the last segment, $T_{\ell j}$. Output 2 is the total rate of enthalpy change of water computed from

$$Q = F\, c_\ell\, (T_{\ell 1} - T_{\ell J}) \quad (17\text{–}42)$$

Output 3 is net radiation above the cover computed from equation 17–40 and summed over all segments. Outputs 4 and 5 are rates of sensible and latent heat convected from the air to the cover. They are computed from equations 17–19 and 17–21 and summed for all segments.

Type 18 Evaporative Air Cooler

The type 18 evaporative air cooler is one of the simplest devices (fig. 1). It is characterized by specifying a maximum air flow rate, M_{max} (kg/s), as parameter 1 and an effectiveness or saturation efficiency, η, as parameter 2. See appendix E for parameter, input and output codes.

The outlet flow rate M_o, is computed first as the product of M_{max} and a control variable, γ:

$$M_o = \gamma M_{max} \quad (18\text{–}1)$$

The control variable γ (input 4) can be supplied by a type 4 thermostat or similar device.

The outlet dry bulb temperature, T_{do}, is computed next using the definition of effectiveness, η, (Kimball et al. *1977*) from

$$T_{do} = T_{di} - \eta(T_{di} - T_{wi}) \quad (18\text{–}2)$$

where T_{di} is the inlet dry bulb temperature and T_{wi} is the inlet wet bulb temperature, which are available for outside conditions from the type 1 reader. When $M_o = 0$, T_{do} is set equal to T_{di}.

To make the cooler compatible with other MEB models, the outlet humidity ratio, W_o, is also calculated. First the saturation vapor pressure at wet bulb temperature is obtained using Tentens' equation (Murray *1967*):

$$p^* = 0.61078\exp[17.2694T_{wi}/(T_{wi} + 237.30)] \tag{18–3}$$

Then, the saturation humdity ratio at T_{wi} is computed from p^* and the barometric pressure, P (ASHRAE *1972*, p. 99):

$$W^* = 0.62198p^*/(P - p^*) \tag{18–4}$$

Finally, the outlet humidity ratio, W_o, is calculated from (ASHRAE *1972*, p. 100):

$$W_o = \frac{W^*(2{,}468 \times 10^3 - 2{,}328T_{wi}) - 1{,}005(T_{do} - T_{wi})}{2{,}468 \times 10^3 + 1{,}859T_{do} - 4{,}168\ T_{wi}} \tag{18–5}$$

The rate of evaporation of water in the cooler, E (kg/s), is calculated from the change in humidity ratio of the air as it passes through the cooler. First the inlet humidity ratio, W_i, is calculated using T_{di} instead of T_{do} in equation 18–5. Then,

$$E = M_o(W_o - W_i) \tag{18–6}$$

Type 19 Rock Bed

The type 19 rock bed simulates the performance of a rock bed used for thermal energy storage, with air as the heat transfer fluid. The model used is based on that of Mumma and Marvin (*1976*), theirs being more stable and accurate than previous numerical rock bed models. The model assumes that the particle size is small enough so that temperature gradients inside the particles are insignificant, that is, that the Biot number is less than 0.1 (Duffie and Beckman *1974*). A significant enhancement to the model of Mumma and Marvin is the consideration of latent heat transfer. Condensation of moisture can occur on the particles whenever the humidity ratio of the bulk air exceeds the saturation humidity ratio of the air-rock interface, which is at rock temperature. It is assumed that no significant absorption of moisture occurs and that all condensed water drains away. Thus, condensation can occur in the bed but not evaporation.

The following symbols will be used:

A cross-sectional area of rock bed (m^2)
C integration constant
D_r equivalent diameter of individual rocks (m)
E enthalpy (J/kg)
F mass flow rate (kg/s)
G mass flow rate per unit area (kg/s•m^2)
K mass transfer coefficient (kg/s•m^2)
L length of rock bed (m)
N number or rock bed segments
P barometric pressure (kPa)
T temperature (°C)
U loss coefficient (W/m^2•°C)

V volume (m^3)
W humidity ratio (kg H_2O)/kg air)
a rock surface area per volume of rock bed (m^2/m^3)
c specific heat (J/kg•°C)
h heat transfer coefficient (W/m^2•°C)
h_v volumetric heat transfer coefficient (W/m^3•°C)
ℓ length variable (m); $\Delta\ell$ is the length of one segment
p water vapor pressure (kPa)
s length of perimeter around rock bed (m)
t time (s)
ϵ fraction of void space in the rock bed (m^3/m^3)
$\varkappa$ effective thermal conductivity of the rock bed (W/m•°C)
ρ density (kg/m^3)

Subscripts are as follows:

a air
b bottom
e environment
n index for rock bed segments
o outside, or base when referring to enthalpy
r rock
t top
v volumetric
w vaporization

A cross-section of a rock bed is illustrated in figure 19. Mass flows of air can enter the top, F_t, or bottom, F_b, of the rock bed, but not at the same time. For derivation of the equations, F_t will be considered first. The rock bed, which is L meters deep, is considered to be composed of N segments of length $\Delta\ell = L/N$. Partially following Mumma and Marvin (*1976*), the equation for heat transfer from the air to the rocks at any given point in the bed is

$$G_t c_a(-dT_a) = ha(T_a - T_r)d\ell \tag{19–1}$$

where ℓ is the distance in the direction of flow. Similarly, assuming the rocks are completely wetted or completely dry, the equation for mass transfer from air to rock bed is (ASHRAE *1972*, p. 72)

$$G_t(-dW_a) = Ka(W_a - W_r)d\ell \tag{19–2}$$

where

$$W_r = W_r^* \text{ if } W_r^* < W_a$$

$$\text{or } W_r = W_a \text{ if } W_r^* \geq W_a$$

Combining equations 19–1 and 19–2 with the enthalpy of vaporization yields

$$-G_t(c_a\, dT_a + E_{wo} dW_a) = [Ka(W_a - W_r)E_w + ha(T_a - T_r)]d\ell \tag{19–3}$$

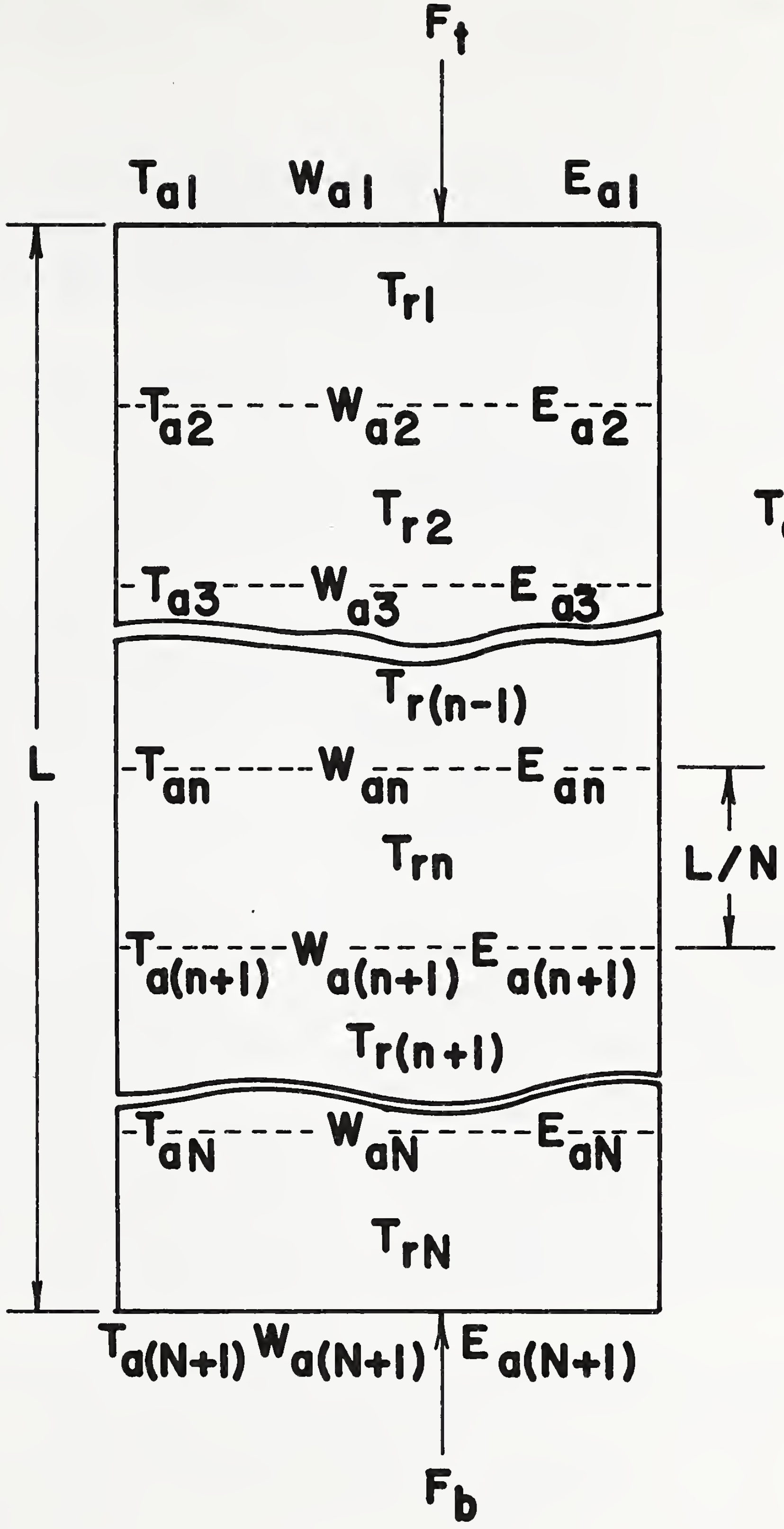

Figure 19.
Cross section through a type 19 rock bed. The *T, W, E,* and *F* refer to temperature, humidity ratio, enthalpy, and mass flow, respectively.

Using the Lewis relation, $h = Kc_a$, and the definition of enthalpy for air, equation 19–3 reduces to

$$-G_t dE_a = Ka(E_a - E_r)d\ell \qquad (19\text{–}4)$$

Equation 19–4 equates the rate of change in enthalpy of the air to the rate of enthalpy transfer from the air to the rock surfaces, where E_r is the enthalpy of the air at the rock-air interface at rock temperature, and E_a is the enthalpy of the bulk air in the voids between the rocks. Following Mumma and Marvin, equation 19–4 can be rearranged with the variables separated:

$$\frac{dE_a}{d\ell} - \frac{Ka}{G_t} E_a = \frac{Ka}{G_t} E_r \qquad (19\text{–}5)$$

The solution to equation 19–5 is

$$E_a = E_r + C\exp(-Ka\ell/G) \qquad (19\text{–}6)$$

Equation 19–6 is valid for any point in the rock bed; but the rock enthalpy, E_r, varies continuously through the bed. If the segmentation scheme illustrated in figure 19 is utilized and the segments are short enough so that E_r is effectively a constant within each individual segment, then the integration constant, C, can be evaluated. For the nth segment, the air enters at a relative distance of $\ell = 0$ with an enthalpy of E_{an}. Substituting this boundary condition into equation 19–6, C is found to be $E_{an} - E_{rn}$. Then, at $\ell = \Delta\ell$, the air exits the segment with an enthalpy, $E_{a(n+1)}$, given by

$$E_{a(n+1)} = E_{rn} + (E_{an} - E_{rn})\exp(-Ka\Delta\ell/G) \qquad (19\text{–}7)$$

Starting at the end where the air enters, equation 19–7 provides the means to compute the change in enthalpy of the air as it passes through the rock bed from segment to segment. However, the changes in temperature and humidity ratio are more useful, and they can be obtained from the enthalpy change. The assumptions have been made that the segments are small enough that the rock temperature is effectively a constant within a segment and that the rocks are small enough so that the rock-air interface is at rock temperature. From the analysis for direct-air-water-contact equipment (ASHRAE *1972*, p. 22), the air must follow a straight line on an enthalpy-temperature diagram from its state at the beginning of a segment toward the state of the air-rock interface. Therefore, the temperature change through a segment must be proportional to the enthalpy change, or mathematically,

$$\frac{T_{a(n+1)} - T_{rn}}{T_{an} - T_{rn}} = \frac{E_{a(n+1)} - E_{rn}}{E_{an} - E_{rn}} = \exp(-K_a\Delta\ell/G) \qquad (19\text{–}8)$$

Solving for the temperature of the air exiting segment n,

$$T_{a(n+1)} = T_{rn} + (T_{an} - T_{rn})\exp(-K_a\Delta\ell/G) \qquad (19\text{–}9)$$

Consequently, the exit humidity ratio can be obtained from the defining equation for enthalpy:

$$W_{a(n+1)} = \frac{E_{a(n+1)} - 1{,}005T_{a(n+1)}}{2.468 \times 10^6 + 1{,}859T_{a(n+1)}} \qquad (19\text{–}10)$$

The preceding equations all pertain to the change in state of the air as it passes through the rock bed. Of course, the enthalpy gained or lost by the air will cause the rock temperature to change. An energy balance can be written for the rocks in each segment.

The rate of energy addition to rocks equals the following:

+ the rate of enthalpy change of the air passing through segment
− the rate of loss to the surrounding environment
− the rate of conduction of heat to the next segment
+ the rate of conduction of heat from the preceding segment,

or, mathematically,

$$\begin{aligned} A\Delta\ell(1-\epsilon)\rho_r c_r(dT_{rn}/dt) = {} & +G_t A(E_{an} - E_{a(n+1)}) \\ & - U\Delta\ell s(T_{rn} - T_e) \\ & - \kappa A(T_{rn} - T_{r(n+1)})/\Delta\ell \\ & + \kappa A(T_{r(n-1)} - T_{rn})/\Delta\ell \end{aligned} \qquad (19\text{–}11)$$

From equation 19–11 the rate of temperature change of the nth segment, dT_{rn}/dt, is obtained. The same equation applies to all segments except the top and bottom. For these segments the areas of the ends in the environmental loss terms are $\Delta\ell s + A$; and, of course, there is no conduction from another segment above the top or from below the bottom. The values of dT_{rn}/dt for all the segments are returned to the main program, which performs the integration and computes new estimates of the rock bed temperatures, T_{rn}, as described in the main program section.

The air flow was assumed to be from top to bottom in the derivation of the previous equations. Equivalent equations for flow from bottom to top have been written, and they also are incorporated in subroutine ROCK. This capability allows the user to take the advantage of temperature stratification in the bed by reversing flows between charging and discharging the bed.

The required parameters and inputs are listed in appendix E. Most are self-explanatory, but some need more elaboration. Parameter 5 is the equivalent diameter of the individual rocks, D_r. It is defined by

$$D_r = (6V_r/\pi)^{1/3} \qquad (19\text{–}12)$$

where V_r is the average volume of an individual rock. The rock diameter is used to compute the volumetric heat transfer coefficient, h_v (W/°C•m^3 of rock bed), which is the product of the more ordinary area-based heat transfer coefficient, h (W/°C•m^2 of heat transfer area), and the amount of surface area of rock for heat exchange per unit volume of rock bed, a (m^2/m^3):

$$h_v = ha \tag{19–13}$$

Subroutine ROCK uses equation 19–14, from Löf and Hawley (*1948*), to compute h_v:

$$h_v = 650(G/D_r)^{0.7} \tag{19–14}$$

Duffie and Beckman (*1974*) suggested using equation 19–14, and Mumma and Rodriguez-Anza (*1979*) reported good agreement between temperatures it predicted and measured temperatures in their rock bed.

Equation 19–14 also contains the mass flow rate per unit of bed area, G (m^2), so the rate of heat transfer is flow-rate dependent. If the flows entering the top, F_t, or bottom, F_b, are controlled by type 4 thermostats, then they are average flows for a simulation time increment. In actuality, the bed more likely would be cycled on, off, on, off, several times rather than have some steady average flow. The heat exchange would occur only during the portion of the time the bed has maximum flow through it; and, therefore, the G in equation 19–14 must be based on the maximum flow rate. Therefore, subroutine ROCK requires value of γ_t and γ_b as inputs 7 and 8. These control variables are the same ones that would control the fans supplying F_t and F_b. The value of G to be used in equation 19–14 is obtained by dividing F_t or F_b, whichever is larger, by its corresponding γ and the cross-sectional area of the bed.

After h_v has been computed, the volumetric mass transfer coefficient, $K_v = Ka$, is obtained by dividing h_v by the humid specific heat of the air, c_a (J/kg•°C):

$$c_a = 1{,}005 + 1{,}895W \tag{19–15}$$

The value of W used in equation 19–15 is W_{a1} if the flow is from top to bottom or $W_{a(N+1)}$ for the reverse.

Parameter 6 is the effective volumetric heat capacity of the rock bed, c_{rv}. It is the product of the specific heat of the solid rock, c_r (J/kg•°C), the density of the solid rocks, ρ_r (kg/m^3), and one minus the fraction of the bed that is void space (or air):

$$c_{rv} = c_r\rho_r(1 - \epsilon) \tag{19–16}$$

Saturation humidity ratios are computed from

$$W^* = 0.62198p^*/(P_o - p^*) \tag{19–17}$$

where the saturation vapor pressure, p^* (kPa), are computed from Tetens' equation (Murray *1967*):

$$p^* = 0.61078\exp(17.2694T/(T + 237.30)) \tag{19–18}$$

As listed in appendix E, the temperatures and humidity ratios of the air streams leaving the bottom or top of the bed are outputs from the type 19 rock bed. From the total change in ethalpy and humidity ratio of the air passing through the bed, the rates of energy addition to the bed and the rates of water condensation in the bed for the two streams are output separately also. In addition, the temperatures of the rocks in all the individual segments are outputs.

Type 20 Arithmetic Calculator

The type 20 arithmetic calculator is also adapted from Klein et al. (*1976*). It is a useful device for scaling output, for combining control signals, and for many other manipulations. It works like a reverse-polish logic calculator with an operational stack. The parameters are coded operational commands analogous to keystroke commands which direct the calculator to perform arithmetic operations on the inputs. The code for the operations are as follows:

0 *Enter.* The value of the next input is placed on the stack.
1 *Multiply.* The two values on top of the stack are replaced with their product.
2 *Divide.* The two values on top of the stack are replaced by their quotient. The value entered last is divided into the previous value.
3 *Add.* The two values on top of the stack are replaced by their sum.
4 *Subtract.* The two values on top of the stack are replaced by their difference. The value entered last is subtracted from the previous value.
5 *Exponentiate.* The two values on top of the stack are replaced by the previous value raised to the power given by the most recent entry.
6 *Log_{10}.* The top value in the stack is replaced by $\log_{10}$ of itself.
7 *Negate.* The top value in the stack is replaced by the negative of itself.
8 *Select Positive.* The top value in the stack is left unchanged unless it is negative, in which case it is replaced by 0.
9 *Logical OR.* The larger of the two highest values becomes the top value of the stack.
10 *Logical AND.* The smaller of the two highest values becomes the top value of the stack.
−1 *Constant.* The value of the next parameter is placed on top of the stack as a constant.

After all of the parameter operations have been performed, the value on the top of stack becomes output 1. Output 2 is equal to 1 minus output 1 and is useful when a simultaneous reverse logic value is needed for control signal manipulations.

There is one special case. If the first operational command is not 0 or −1, ARITH assumes that there are two inputs and only the one command.

As listed in appendix E, the first parameter is the total number of parameters, the second parameter is the number of inputs, and the third and subsequent parameters are the sequence of operational commands and constants. The use of ARITH can best be illustrated by examples.

Example 1. A latent energy flux in watts needs to be divided by 2.44×10^6 to obtain the equivalent water flux in kilograms per second. The single input, X_1, is the latent energy flux. The parameters needed to accomplish the conversion are

5, 1, −1, 2.44E6, 2

Example 2. Four inputs needed to be summed. The required parameters are

9, 4, 0, 0, 0, 0, 3, 3, 3

or

9, 4, 0, 0, 3, 0, 3, 0, 3

or

9, 4, 0, 0, 3, 0, 0, 3, 3

Example 3. The ratio X_1/X_2 needs to be obtained. The inputs must be in the order

X_1, X_2

The parameters to accomplish the division would be

5, 2, 0, 0, 2

or taking advantage of the special two-input case the parameters could also be

3, 2, 2

Type 21 On-Off Thermostat

This thermostat is a simple on-off device. When the temperature (or other variable) given as input 1 is less than a set point, given as parameter 1, the value of output 1 is set equal to 1.0 and the value of output 2 is set equal to 0.0. When the temperature is greater than or equal to the set point, outputs 1 and 2 are set equal to 0.0 and 1.0, respectively.

If the value of parameter 2 is 2, a differential mode is used and the set point is compared with input 1 minus input 2.

Because the type 21 on-off thermostat is either on or off, it can oscillate from on to off with successive iterations. The user should be aware of this potential problem and, if necessary, can use the more complicated type 4 thermostat, which is a proportional controller.

Type 22 Multistage Thermostat

The type 22 multistage thermostat is an extention of the type 4 thermostat. A type 4 thermostat controls proportionally, based on the history of responses to calls on previous iterations. When several type 4 thermostats are used to control several heating and cooling stages, occasionally the model may become unstable. Instability can occur when outside temperatures change rapidly from one simulation time to the next. Under such conditions, control, which should shift from one stage to the next, may not do so. Instead, two or more of the type 4 thermostats may attempt to control proportionally such that they effectively fight each other, and convergence cannot be attained. The type 22 multistage thermostat is like several type 4 thermostats but has additional logic to resolve conflicts between stages, and only one stage is allowed to control proportionally at a time.

As listed in appendix E, each stage has its own set point, and there can be up to 10 stages. Parameter 1 is the total number of parameters which equals the number of

stages, N, plus 2. Parameter 2 is a master set point, T_{SM}, that divides heating from cooling stages. It can be anywhere between the warmest set point for controlling heaters and the coolest set point for controlling coolers. Parameters 3 through $N+2$ are the set point temperatures from coldest to warmest for the various stages.

The type 22 multistage thermostat has one input, T_i, the temperature of the structure or space that is being heated or cooled by the several devices controlled by the type 22 thermostat.

The type 22 multistage thermostat has two outputs for each stage, as listed in appendix E and illustrated in figure 20. Outputs 1 and 2 are for the coldest stage, 3 and 4 for the second coldest, and so forth until $2N-1$ and $2N$ for the warmest. The even outputs are 1 minus the corresponding odd outputs. The odd outputs should be used for controlling heaters and the even for controlling coolers.

The criteria used to resolve conflicts are the following. First, all control variables more than one stage away from T_i must be fully off or on (0 or 1). That is if $T_{sn} < T_i < T_{s\,(n+1)}$, then all the odd (heater) outputs for stages below n are set equal to 0 and all the odd outputs for stages above $n+1$ are set equal to 1. Second, if T_i falls between two stages and one of those stages already is controlling proportionally, that stage will be allowed to continue to control proportionally and the other will be

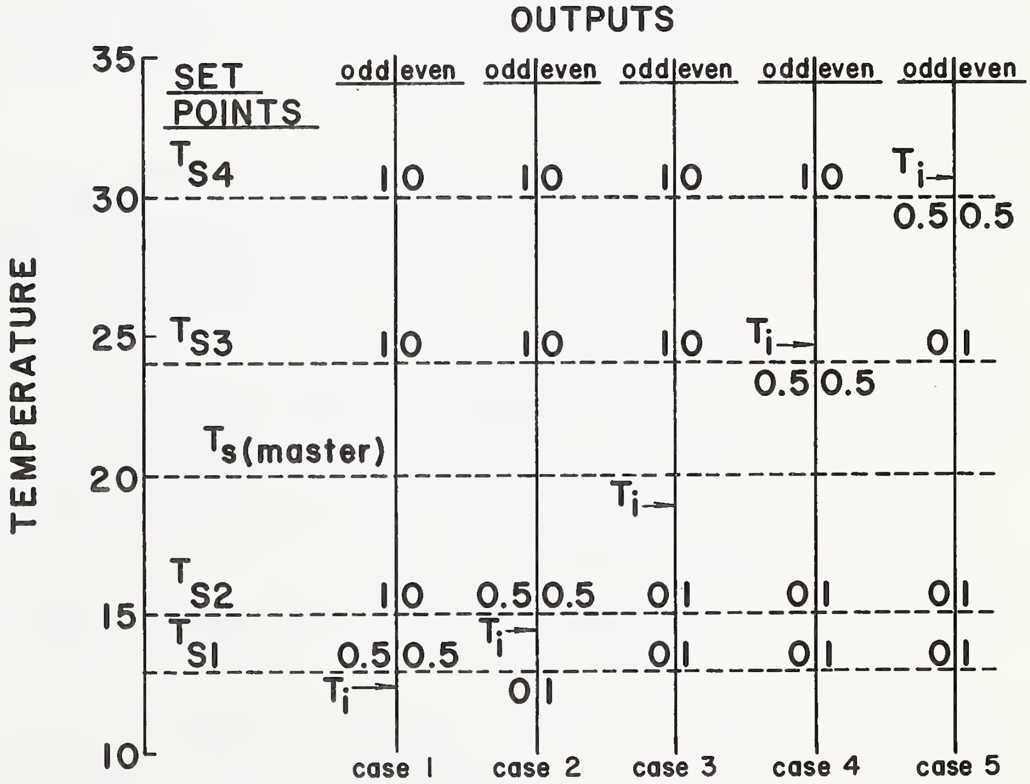

Figure 20.
Illustration of typical outputs from a type 22 multistage thermostat which has four stages: two for heating and two for cooling. Each stage has its own set point, T_{sn}, and a master set point, $T_{s(master)}$, divides heating from cooling. Five cases are shown with a different input temperature, T_i, for each case.

left in the same state. The third, fourth, and fifth criteria all pertain to having both stages adjacent to T_i trying to control proportionally. Third, if T_i falls between the warmest heating and the coolest stages as defined by T_{sm}, then the proportional control will be given to the stage having the larger value of the control variables, and the other stage will be turned off (odd output if heating stage and even output if cooling stage). Fourth, if T_i falls between two heating stages, proportional control will be given to the warmer stage and the cooler stage will be turned off (odd output = 0). Fifth, if T_i falls between two cooling stages, proportional control will be given to the cooler stage and the warmer stage will be turned off (even output = 0).

The action of the type 22 multistage thermostat is illustrated in figure 20 for five different values of the input temperature, T_i. For the first case T_i is colder than the coolest set point, T_{s1}. The stage is controlling proportionally with its heater operating at 0.5 of capacity. The second stage heater for T_{s2} is fully on, as indicated by the odd output being 1. There are two cooling stages with set points T_{s3} and T_{s4} above the master set point, and these coolers are fully off as indicated by the even outputs being 0. As T_i warms above T_{s1} for case 2, the T_{s1} heater is turned off (odd output = 0), and T_{s2} controls proportionally. Further warming above T_{s2} for case 3, places T_i in the band between heating (T_{s2}) and cooling (T_{s3}). As mentioned for the third criterion in the previous paragraph, control will be given to the larger of the control variables for these two stages and only it can control proportionally. However, when T_i stays between these two set points on consecutive iterations, either heating or cooling devices will soon be turned off, as shown in figure 20, which has 0 for the odd heating stage outputs and also 0 for the even cooling stage outputs. For cases 4 and 5, T_i has increased to be above the cooling set points. The heater stages are fully off, and now the cooling stages control proportionally—T_{s3} for case 4 and T_{s4} for case 5.

Type 23 Curtain Heat Exchanger

The type 23 curtain heat exchanger simulates the performance of a curtain heat exchanger like the one described by Simpkins et al. (*1978*). The actual heat exchanger consists of a sheet of plastic film draped over a water distribution pipe. Warm or cool water oozes out of holes in the distribution pipe and runs down the inside surfaces of the plastic. The outside surfaces exchange energy with the air in the greenhouse or other space. The assumption is made that solar radiation absorption is negligible and implies that the exchanger is used only at night or is highly reflective if used during the day. The energy is exchanged physically by convection of sensible and latent heat and by thermal radiation to and from other surfaces in the greenhouse. However, the type 23 exchanger merely uses an overall heat transfer coefficient to compute the total heat transfer rate due to all the combined heat transfer mechanisms.

The equation to describe the rate of transfer of energy from the space to the exchanger, Q (W), is

$$Q = UA\ (T_{ai} - \overline{T}_w) \tag{23–1}$$

where U = overall heat transfer coefficient (W/m² · °C) (parameter 2)
A = heat exchange area of curtain (m²) (parameter 1)
T_{ai} = air temperature of space (°C) (input 1)
$\overline{T}_w$ = average temperature of water in exchanger (°C)

The rate at which the water is absorbing energy can also be determined from the rate of temperature change of the water:

$$Q = m_w c_w (T_{wo} - T_{wi}) \qquad (23\text{–}2)$$

where m_w = mass flow rate of the water (kg/s) (input 5)
c_w = specific heat of water (4,190 J/kg ·°C)
T_{wi} = inlet water temperature (°C) (input 4)
T_{wo} = outlet water temperature (°C)

Because $\bar{T}_w = (T_{wi} + T_{wo})/2$, equations 23–1 and 23–2 can be combined and rearranged to obtain the outlet water temperature:

$$T_{wo} = \frac{T_{wi}(R - 1/2) + T_{ai}}{R + 1/2} \qquad (23\text{–}3)$$

where $R = (m_w c_w)/(UA)$

The other types of heat exchangers are of the forced convection type with a given air mass flow rate; and the greenhouse models have been written to accept external fluxes of energy, given the temperature, mass flow rate, and humidity ratio of the entering air mass. Therefore, to make the type 23 curtain heat exchanger compatible with the other MEB subroutine models, an imaginary outlet air flow rate, m_a, of 1 kg/s is generated, and then a corresponding imaginary outlet air temperature, T_{ao}, is computed from

$$T_{ao} = T_{ai} - Q/(m_a c_a) \qquad (23\text{–}4)$$

where c_a is the specific heat of humid air taken to be 1,020 J/kg·°C. Using the T_{ao} and m_a computed by subroutine CXR, the other subroutine models have enough information to decode the rate of energy exchange between the greenhouse air and the curtain heat exchanger.

Type 24 Passive Storage

The type 24 passive storage simulates the performance of a stack of water-filled bottles or other sensible heat storage material, such as rocks. The thermal conductivity, $\varkappa$, of the material must be large enough or the effective radius, R, small enough that internal temperature gradients are insignificant. This criterion is met if the Biot number ($hR/\varkappa$) is less than 0.1 (Duffie and Beckman *1974*), where h is the heat transfer coefficient from the surroundings to the material. For liquids like water, natural convection in the liquid can make the effective value of the thermal conductivity larger than the handbook thermal conductivity due to molecular oscillations. It is assumed that the type 24 passive storage does not absorb solar radiation directly. Obviously, more energy can be collected and stored if the storage material is exposed directly to the sun. However, for every photon of visible solar radiation entering a greenhouse without absorption by a green leaf, there is a consequent reduction in yield. Therefore, this model assumes that the energy is exchanged by convection of sensible and latent heat and by thermal radiation to and from other surfaces in the greenhouse. The model uses a constant, overall heat-transfer coefficient to compute the total heat transfer rate due to all the combined heat transfer mechanisms.

The equation to describe the rate of transfer of energy from the bulk air to the exchanger, Q (W), is

$$Q = UA(T_{ai} - T_s) \tag{24-1}$$

where U = overall heat transfer coefficient (W/m²·°C) (parameter 1)
A = total area available for heat exchanges (m²) (parameter 2)
T_{ai} = air temperature of space (°C) (input 1)
T_s = temperature of storage material (°C) (dependent variable 1)

This rate must equal the rate of energy storage, as indicated by the rate of temperature change of the material:

$$Q = M_s c_s (dT_s/dt) \tag{24-2}$$

where M_s = total mass of storage material (kg)
c_s = specific heat of storage material (J/kg·°C)
t = time (s)

Combining equations 24–1 and 24–2 and rearranging, the rate of temperature change of the material is

$$\frac{dT_s}{dt} = \frac{UA}{M_s c_s}(T_{ai} - T_s) \tag{24-3}$$

The value of dT_s/dt computed from equation 24–3 is returned to the main program for integration with the internal integrator in MEB.

Most of the external devices that exchange energy with the greenhouse air in the greenhouse models are of the forced convection type, with a given air mass flow rate. To make the type 24 passive storage compatible with these greenhouse models, and imaginary outlet air flow rate, m_a, of 1 kg/s is generated by subroutine PSTOR; and then a corresponding imaginary outlet air temperature, T_{ao}, is computed using

$$T_{ao} = T_{ai} - Q/(m_a c_a) \tag{24-4}$$

where c_a is the specific heat of humid air taken to be 1,020 J/kg·°C. Using the T_{ao} and m_a computed by subroutine PSTOR, the other subroutine models have enough information to decode the rate of energy exchange between the greenhouse air and the storage material.

Simple Conventional Greenhouse

An example of the use of MEB to predict the fossil energy needed for a simple conventional greenhouse on a winter day will be presented in this section. The greenhouse system is illustrated in figure 2 and includes a type 15 simple greenhouse, a type 22 multistage thermostat, and a type 16 heater for the essential mechanical devices. Also included are a type 1 reader, a type 13 reservoir, a type 20 arithmetic calculator, a type 2 integrator, and a type 3 printer as conceptual devices to facilitate the computations.

Figures 21 through 24 illustrate the development of file MEBDI for this system. As detailed in "Instructions for Use," the first line of the file in figure 21 is an alphanumeric title which contains no commas. The next two lines are the file name and device code where the input will be read and the output will be written, respectively. The fourth line shows that the simulation is to start with data from 1978, March, 7th day, at 0000 hours; the time step is 1.0 hour; the total number of times that simulations are to be performed is 25; and no trace is to be printed, as indicated by the nontime −1 for the first and last traces.

The total number of units is eight in line 5, with unit 1 as the type 1 reader. It has no parameters (PAR), inputs (IN), or derivatives that require initial values for the dependent variable (T); so these three lines are omitted. It does have 23 outputs (OUT), as listed in appendix E, and these must be initialized. However, because the reader is unit 1 and will be called first, these initial output values will not be used and can be initialized to anything, such as the 1's in figure 21.

Unit 2 is the type 13 reservoir, which also has no inputs or derivatives. This reservoir is to be used for supplying a constant value of 0.0 to some of the inputs of the greenhouse model; so its single output is initialized to 0.0. It has two parameters, the first being the total number of parameters (2), and the second being the desired output value (0.0). Because the type 13 reservoir is a device which has a variable number of parameters, the first one must be separated from the rest with a carriage return.

Unit 3 is the type 15 simple greenhouse, which has so many parameters that a special form is used, as illustrated in figure 22. The parameters define a small conventional fiberglass greenhouse whose test values are listed in appendix E. The first input is solar radiation, which requires the expression "1, 12" to connect it to unit 1, the type 1 reader, whose 12th output is solar radiation. Similar connections to unit 1 are made for wind speed, U_{ao}, pressure, P_{ao}, outside dry bulb air temperature, T_{ao}, and wet bulb temperature, T_{wb}. For this example, the properties of the greenhouse wall will not change, and natural ventilation will not be used; so both γ_c and γ_N must be fixed at zero. This can easily be accomplished by connecting them to unit 2, output 1, which is the type 13 reservoir that was made to have 0.0 for an output. The type 15 greenhouse has its own powered ventilation system which should be turned on if the temperature rises above 26.5°C. Therefore, input 7, γ_p, is connected to output 4 of the type 22 multistage thermostat. The greenhouse is also to be heated, so

inputs 9 and 10 are connected to outputs 1 and 2 of the type 16 heater. The heater is the only external device, so parameter 1 is 1, and the total number of inputs is 10. Output 1, from the greenhouse inside-air temperature, is initialized to 15.5°C, and the other outputs are initialized to 1's, but actually none of the outputs are used by a device with a smaller unit number than that of the greenhouse itself.

MODULAR ENERGY BALANCE MODEL INPUT DATA (MEBDI)

RUN TITLE: SIMPLE CONVENTIONAL GREENHOUSE EXAMPLE (7MAR78)

WEATHER FILE: P837

OUTPUT FILE: 6

YR(2)	STARTING TIME MON	DAY	HR(.)	TIME INCRE	NO. TIMES	FIRST TRACE	LAST TRACE
78	3	7	0.0	1.0	25	-1	-1

NO. UNITS : 8

UNIT		1 2 3 4 5 6 7 8 9 10 11 12 13 14
1	TYPE:	1, READER
	PAR:	
	IN:	
	OUT:	1,1, 1,1, 1,1, 1,1, 1,1, 1,1, 1,1, 1,1, 1,1, 1,1, 1,1, 1
	T:	
2	TYPE:	13, RESERVOIR
	PAR:	2 / 0.0,
	IN:	
	OUT:	0.0,
	T:	
3	TYPE:	15, Greenhouse - see attached form (Fig. 22)
	PAR:	
	IN:	
	OUT:	
	T:	
4	TYPE:	22, MULTISTAGE THERMOSTAT
	PAR:	4 / 20, 15.5, 26.5,
	IN:	3,1,
	OUT:	0.5, 0.5, 1, 0,
	T:	
5	TYPE:	16, HEATER
	PAR:	6850, 0.26, 0.0,
	IN:	3,1, 2,1, 2,1, 4,1,
	OUT:	40, 0.13, 0,
	T:	
6	TYPE:	20, ARITH - FOSSIL ENERGY USE RATE (MJ/(S M2))
	PAR:	14 / 2, 0, -1, 6850, 1, 0, -1, 1200, 1, 3, -1, 27.E6, 2
	IN:	4,1, 4,4,
	OUT:	0, 1,
	T:	
7	TYPE:	2, INTEGRATOR
	PAR:	1, 24, 7,
	IN:	6,1,
	OUT:	0,
	T:	

Figure 21.
Completed data form for units 1 through 7 of file MEBDI for simple conventional greenhouse example.

TYPE 15 SIMPLE GREENHOUSE DATA

UNIT No.: 3

PARAMETERS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
J	A_c	A_g	v_{ai}	f_λ	b_{20}	b_{30}	b_{21}	b_{31}	U_{Max}	η	ρ_{vg}	τ_{s0}	b_{00}	b_{10}	τ_{s1}
1	62	27	73	0.5	0.23	0.08	0.0	9.0	156	0.75	0.14	0.66	8.8	1.6	0.66

17	18
b_{01}	b_{11}
8.8	1.6

INPUTS

1	2	3	4	5	6	7	8
S_o	U_{ao}	P_{ao}	T_{ao}	T_{wb}	γ_c	γ_p	γ_N
1 12	1 7	1 8	1 9	1 10	2 1	4 4	2 1
9	**10**	**11**	**12**	**13**	**14**	**15**	**16**
T_{x1}	M_{x1}	T_{x2}	M_{x2}	T_{x3}	M_{x3}	T_{x4}	M_{x4}
5 1	5 2						

INITIAL OUTPUT GUESSES

1	2	3	4	5	6
T_{ai}	S_i	ΣX_j	C	V_s	V
15.5	1	1	1	1	1

2 THROUGH 6 CAN USUALLY BE 1's

Figure 22.
Completed data form for the type 15 simple greenhouse in the simple conventional greenhouse example.

Unit 4 is a type 22 multistage thermostat with the master, heating, and cooling set points at 20, 15.5, and 26.5°C. This is also a device with a variable number of parameters, so the first parameter—the total number of parameters (4)—must be on a line by itself, followed by a carriage return. The initial outputs are chosen to indicate a guess that at the initial time, which is midnight on a winter night, the heater will be operating at 0.5 capacity and the power ventilation system will be off. Again, however, no device in this system that has a unit smaller than that of the thermostat itself uses these outputs, so any numbers could have been used for initialization.

Unit 5 is the type 16 heater, which was discussed in some detail in "Instructions for Use." The only additional point to be made here is that the initial values of outputs 1 and 2 are used by the greenhouse the first time it is called. Therefore, the initial values of these two outputs should be reasonable, as indicated by the estimate of output temperature of 40°C and a flow rate at half capacity of 0.13 kg/s.

Unit 6 is a type 20 arithmetic calculator, which is being used to calculate the total fossil energy consumption rate of the system and convert it to convenient units. The fossil energy consumers in this system are the heater and the fan in the ventilation system of the greenhouse. The heater is rated at 6850 W, as specified in parameter 1 of the type 16 heater. The fan is sized to provide a maximum 156 air changes per hour (parameter 10 of the type 15 greenhouse), which is 3.16 m^3/s and would require a motor of about 1,200 W capacity. The fraction of the time that the heater and fan actually operate is determined by their respective control variables, which are outputs 1 and 4 from unit 4, the multistage thermostat. Convenient units for daily energy totals on a unit area basis are megajoules per square meter (MJ/m^2), so the energy use rate must be divided by 10^6 to convert from watts (=J/s) to megajoules per sec-

MEB MODEL INPUT DATA - CONTINUED

UNIT		1	2	3	4	5	6	7	8	9	10	11	12	13	14
8	TYPE:	3, PRINTER													
	PAR:	12	1	80	8										
	IN:	1,1	1,2	1,3	1,4	1,12	1,9	1,10	3,1	4,1	4,4	6,1	7,1		
	OUT:														
	T:														
9	TYPE:														
	PAR:														
	IN:														
	OUT:														
	T:														
10	TYPE:														
	PAR:														
	IN:														
	OUT:														
	T:														
11	TYPE:														
	PAR:														
	IN:														
	OUT:														
	T:														
12	TYPE:														
	PAR:														
	IN:														
	OUT:														
	T:														
13	TYPE:														
	PAR:														
	IN:														
	OUT:														
	T:														
14	TYPE:														
	PAR:														
	IN:														
	OUT:														
	T:														
15	TYPE:														
	PAR:														
	IN:														
	OUT:														
	T:														
16	TYPE:														
	PAR:														
	IN:														
	OUT:														
	T:														

PRINTER: b-YR b MON b DAY b-HR b-SO b TAO b TWB b TAI b GIS b G26 b--Q b-AQ b---b---
LABELS: b---b---b---b---b---b---b---b---b---b---b---b---b---b---

Figure 23.
Completed data form for unit 8 of file MEBDI for simple conventional greenhouse example.

```
SIMPLE CONVENTIONAL GREENHOUSE EXAMPLE  (7MAR78 DATA)   FILE ISCGX
P837
6
78,  3,  7, 0.0, 1, 25,   0,0
8
1, READER                                                    UNIT 1
1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1
13, RESERVOIR                                                UNIT 2
2
0.0
0.0
15, GREENHOUSE                                               UNIT 3
1, 62, 27, 73, 0.5, 0.23, 0.08, 0.0, 9.0, 156, 0.75, 0.14, 0.66, 8.8/
 1.6, 0.66, 8.8, 1.6
1, 12, 1,7, 1,8, 1,9, 1,10, 2,1, 4,4, 2,1, 5,1, 5,2
15.5, 1,1,1,1,1
22, MULTISTATGE THERMOSTAT                                   UNIT 4
4
20, 15.5, 26.5
3,1
0.5, 0.5, 1,0
16, HEATER                                                   UNIT 5
6850, 0.26, 0.0
3,1, 2,1, 2,1, 4,1
40, 0.13, 0.0
20, ARITH - COMPUTE FOSSIL ENERGY USE RATE (MJ/(S M2))       UNIT 6
14
2, 0, -1, 6850, 1, 0, -1, 1200, 1, 3, -1, 27.E6, 2
4,1, 4,4
0,1
2, INTEGRATOR                                                UNIT 7
1, 24, 7
6,1
0
3, PRINTER                                                   UNIT 8
12, 1, 80, 8
1,1, 1,2, 1,3, 1,4, 1,12, 1,9, 1,10, 3,1, 4,1, 4,4, 6,1, 7,1
  YR MON DAY  HR  SO TAO TWB TAI G15 G26   Q  AQ
```

Figure 24.
Listing of file MEBDI for the simple conventional greenhouse example.

ond (MJ/s) and divided also by 27 m^2, the area of the greenhouse, to obtain the unit area basis. Using the notation <*a*,*b*> to indicate output *b* from unit *a*, the total fossil energy use rate, *Q* (MJ/m^2•s), is

$$Q = (6{,}850.* <4,1> + 1{,}200* <4,4>)/27.E6$$

Referring to unit 6 in figure 21, *Q* is evaluated by the type 20 arithmetic calculator as follows: First, parameter 1 is the total number of parameters (14) and is followed by a carriage return because this is a device with a variable number of parameters. Then, parameter 2 indicates there will be two inputs (the <4,1> and <4,4>). Next, a 0

for parameter 3 places the value of input 1 on the stack; a −1 for parameter 4 puts the next parameter (6,850) on the stack; and a 1 for parameter 6 multiplies 6,850*<4,1>. Parameters 7 through 10 do the same for the fan. Finally, the 3 for parameter 11 adds the rates for the heater and fan together, and then the −1, 27.E6, and 2 for parameters 12, 13, and 14 convert from watts to the desired units (MJ/s•m^2).

Unit 7 is the type 2 integrator. Parameter 1 shows that it has a single input, <6,1>; parameter 2 shows that it will reset to zero after 24 hours; and parameter 3 is its unit number (7). The integrator multiplies the input, which is in megajoules per square meter second, by the length of the time step (in seconds) and accumulates the products as the simulation proceeds hour by hour. Thus, the output is the accumulated fossil energy use in megajoules per square meter.

Unit 8 is the type 3 printer, and the parameters in figure 23 indicate that there will be 12 inputs; the time between printouts is 1 hour, 80 characters per line is printer width; and the unit number is 8. Of particular note in figure 23 is the correspondence between the inputs and the print labels at the bottom of the form. Each input is assigned a label up to three characters long that will be printed beside the corresponding value on the paper from the printer. The meanings of the labels are easily forgotten because of the three-character limit. Also, the same labels may be used with different meanings in other systems or files. Therefore, it is advisable to make a table such as table 2 for each system that is simulated.

Table 2.— Detailed explanation of printer labels for the simple conventional greenhouse example

Printer input No.	Label	Item	From— Unit No.	From— Output No.
1	YR	year	1	1
2	MON	month	1	2
3	DAY	day	1	3
4	HR	hour	1	4
5	SO	outside solar radiation (W/m^2)	1	12
6	TAO	outside air temperature (°C)	1	9
7	TWB	outside wet bulb temperature (°C)	1	10
8	TAI	inside greenhouse temperature (°C)	3	1
9	G15	control variable @ 15.5°C	4	1
10	G26	control variable @ 26.5°C	4	4
11	Q	fossil energy use rate (MJ/s•m^2)	6	1
12	AQ	accumulated fossil energy used (MJ/m^2 since integrator last reset)	7	1

Figure 24 shows a listing of file MEBDI as typed into the computer from the forms in figures 21 through 23. Figure 25 shows a sample of weather data from 7 March 1978 for use with this example. This simple example requires only the year, month, day, hour, wind speed, pressure, dry bulb temperature, wet bulb temperature, and total solar radiation on a horizontal surface; so dummy values could have been used for all of the other variables. If a system that requires only a portion of these weather variables is to be simulated, the user may wish to modify the type 1 reader or write a new reader subroutine in order to trim the excess baggage caused by the extra variables.

Figure 26 is a sample of the printout for the simple conventional greenhouse example. The first portion is a printout of the information from the MEBDI file. The user should check such a printout carefully for any mistakes in parameters or in input connections. Mistakes sometimes appear here in the form of I/O errors or in misinterpretation of kinds of devices because the user did not supply the proper number of parameters, inputs, initial outputs, or initial *T* values; or commas and decimal points may be interchanged. The rest of the printout is the hour-by-hour listing of the greenhouse temperature, energy use, and the other information specified in figure 23 and table 2. The hourly energy use and the outside solar radiation are plotted in figure 27.

LOCATION	YEAR	MONTH	DAY	HOUR	DEW POINT	HUMIDITY RATIO	WIND SPEED	PRESSURE	DRY BULB	WET BULB	RELATIVE HUMIDITY	TOTAL S. ON HORIZ.	DIFFUSE ON HORIZ.	ANGLE	TOTAL S. ON VERT.	DIFFUSE ON VERT.	ANGLE	TOTAL S. ON TILT	DIFFUSE ON TILT	ANGLE	SKY RADIATION	8-14 SKY RADIATION	CLOUD COVER
PX	78	3	7	0.0	10.5	0.00818	2.51	97.91	12.9	11.5	85	0	0	90	0	0	90	0	0	90	319	70	0.00
PX	78	3	7	1.0	10.3	0.00805	3.15	97.91	12.6	11.4	85	0	0	90	0	0	90	0	0	90	318	69	0.00
PX	78	3	7	2.0	10.0	0.00789	3.60	97.92	12.2	11.1	86	0	0	90	0	0	90	0	0	90	316	68	0.00
PX	78	3	7	3.0	9.7	0.00771	3.75	97.96	11.6	10.6	88	0	0	90	0	0	90	0	0	90	313	67	0.00
PX	78	3	7	4.0	9.2	0.00749	3.73	97.99	11.0	9.9	89	0	0	90	0	0	90	0	0	90	309	66	0.00
PX	78	3	7	5.0	8.9	0.00731	3.60	98.02	10.6	9.4	90	0	0	90	0	0	90	0	0	90	306	65	0.00
PX	78	3	7	6.0	8.6	0.00718	3.30	98.07	10.4	9.2	89	0	0	90	0	0	90	0	0	90	305	64	0.00
PX	78	3	7	7.0	8.4	0.00707	2.87	98.12	10.4	9.1	87	5	3	87	8	2	81	8	2	82	304	63	0.00
PX	78	3	7	8.0	8.3	0.00703	2.57	98.16	11.1	9.4	83	218	44	75	247	48	73	309	46	67	306	63	0.00
PX	78	3	7	9.0	8.5	0.00710	2.46	98.20	12.8	10.4	76	449	58	64	446	79	65	605	68	53	313	64	0.00
PX	78	3	7	10.0	8.8	0.00725	2.46	98.23	15.2	11.7	66	641	63	53	603	102	59	846	82	38	322	66	0.00
PX	78	3	7	11.0	8.9	0.00729	2.57	98.23	17.2	12.8	58	778	66	45	712	118	54	1017	91	23	330	67	0.00
PX	78	3	7	12.0	8.7	0.00719	2.83	98.20	18.8	13.4	52	849	67	40	770	127	51	1106	96	9	335	67	0.00
PX	78	3	7	13.0	8.2	0.00699	3.22	98.15	20.1	13.7	46	851	67	40	771	127	51	1109	96	8	339	66	0.00
PX	78	3	7	14.0	7.8	0.00677	3.60	98.09	21.1	13.9	42	783	66	45	717	119	54	1024	91	22	341	66	0.00
PX	78	3	7	15.0	7.2	0.00653	4.07	98.04	22.1	14.1	38	650	63	53	610	103	58	857	83	37	344	65	0.00
PX	78	3	7	16.0	6.6	0.00626	4.55	97.99	22.8	14.1	35	461	58	63	456	80	65	620	69	52	345	65	0.00
PX	78	3	7	17.0	6.1	0.00604	4.63	97.96	22.8	13.9	34	232	46	75	259	50	73	327	48	66	343	64	0.00
PX	78	3	7	18.0	5.6	0.00582	3.93	97.99	21.5	13.1	36	10	6	87	18	4	81	18	5	81	337	62	0.00
PX	78	3	7	19.0	5.1	0.00562	2.81	98.05	19.3	11.9	39	0	0	90	0	0	90	0	0	90	327	60	0.00
PX	78	3	7	20.0	5.0	0.00558	2.06	98.09	17.8	11.1	43	0	0	90	0	0	90	0	0	90	321	59	0.00
PX	78	3	7	21.0	5.5	0.00578	2.00	98.14	17.4	11.1	45	0	0	90	0	0	90	0	0	90	321	60	0.00
PX	78	3	7	22.0	6.4	0.00615	2.29	98.17	17.6	11.5	48	0	0	90	0	0	90	0	0	90	324	61	0.00
PX	78	3	7	23.0	7.2	0.00651	2.57	98.19	17.2	11.7	52	0	0	90	0	0	90	0	0	90	325	63	0.00
PX	78	3	8	0.0	7.9	0.00681	2.81	98.21	15.8	11.4	61	0	0	90	0	0	90	0	0	90	322	64	0.00

Figure 25.
Sample weather data in file P837 from Phoenix, AZ, on 3 March 1978. The data are from the National Weather Service, WBAN Surface Observations 144, and have been translated by program DECODER into a format compatible with the type 1 reader. The solar radiation data were simulated using the model of Kimura and Stephenson (*1969*) and the thermal radiation using the model of Kimball et al. (*1982*).

Figure 26.
Sample printout for the simple conventional greenhouse example.

```
                     MODULAR ENERGY BALANCE SIMULATION

SIMPLE CONVENTIONAL GREENHOUSE EXAMPLE  (7MAR78 DATA)   FILE ISCGX
RUN AT 10:09 AM  TUE., 30  NOV., 1982
WEATHER DATA FROM FILE P837

STARTING YR=78. MN= 3. DY= 7. HR=  0.00

INCREMENT  =     1.00 HOURS
NO. TIMES  =       25
FIRST TRACE=    -1.00 HOURS
LAST  TRACE=    -1.00 HOURS
NO. UNITS  =        8


UNIT  1 IS A TYPE  1 READER
PARAMETERS
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
INITIAL OUTPUTS
  1 .1000E+01  2 .1000E+01  3 .1000E+01  4 .1000E+01  5 .1000E+01  6 .1000E+01
  7 .1000E+01  8 .1000E+01  9 .1000E+01 10 .1000E+01 11 .1000E+01 12 .1000E+01
 13 .1000E+01 14 .1000E+01 15 .1000E+01 16 .1000E+01 17 .1000E+01 18 .1000E+01
 19 .1000E+01 20 .1000E+01 21 .1000E+01 22 .1000E+01 23 .1000E+01
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT  2 IS A TYPE 13 RESERVOIR
PARAMETERS
  1 .2000E+01  2 .0000E+00
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
INITIAL OUTPUTS
  1 .0000E+00
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT  3 IS A TYPE 15 SIMPLE GREENHOUSE
PARAMETERS
  1 .1000E+01  2 .6200E+02  3 .2700E+02  4 .7300E+02  5 .5000E+00  6 .2300E+00
  7 .8000E-01  8 .0000E+00  9 .9000E+01 10 .1560E+03 11 .7500E+00 12 .1400E+00
 13 .6600E+00 14 .8800E+01 15 .1600E+01 16 .6600E+00 17 .8800E+01 18 .1600E+01
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
     1   1 12     2   1  7     3   1  8     4   1  9     5   1 10     6   2  1
     7   4  4     8   2  1     9   5  1    10   5  2
INITIAL OUTPUTS
  1 .1550E+02  2 .1000E-01  3 .1000E+01  4 .1000E+01  5 .1000E+01  6 .1000E+01
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT  4 IS A TYPE 22 MULTISTAGE THERMOSTAT
PARAMETERS
  1 .4000E+01  2 .2000E+02  3 .1550E+02  4 .2650E+02
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
     1   3  1
INITIAL OUTPUTS
  1 .5000E+00  2 .5000E+00  3 .1000E+01  4 .0000E+00
INITIAL VALUES OF DEPENDENT VARIABLES
```

```
UNIT  5 IS A TYPE 16 HEATER
PARAMETERS
  1 .6850E+04  2 .2600E+00  3 .0000E+00
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
     1   3  1     2   2  1     3   2  1     4   4  1
INITIAL OUTPUTS
  1 .4000E+02  2 .1300E+00  3 .0000E+00
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT  6 IS A TYPE 20 ARITHMETIC CALCULATOR
PARAMETERS
  1 .1400E+02  2 .2000E+01  3 .0000E+00  4-.1000E+01  5 .6850E+04  6 .1000E+01
  7 .0000E+00  8-.1000E+01  9 .1200E+04 10 .1000E+01 11 .3000E+01 12-.1000E+01
 13 .2700E+08 14 .2000E+01
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
     1   4  1     2   4  4
INITIAL OUTPUTS
  1 .0000E+00  2 .1000E+01
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT  7 IS A TYPE  2 INTEGRATOR
PARAMETERS
  1 .1000E+01  2 .2400E+02  3 .7000E+01
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
     1   6  1
INITIAL OUTPUTS
  1 .0000E+00
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT  8 IS A TYPE  3 PRINTER
PARAMETERS
  1 .1200E+02  2 .1000E+01  3 .8000E+02  4 .8000E+01
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
     1   1  1     2   1  2     3   1  3     4   1  4     5   1 12     6   1  9
     7   1 10     8   3  1     9   4  1    10   4  4    11   6  1    12   7  1
INITIAL OUTPUTS
INITIAL VALUES OF DEPENDENT VARIABLES
  YR MON DAY  HR   SO TAO TWB TAI G15 G26    Q  AQ
TIME =      0.00
  YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .000000E+00   SO .00000
 TAO .129000E+02  TWB .115000E+02  TAI .154280E+02  G15 .301498E+00  G26 .00000
   Q .764913E-04   AQ .000000E+00
TIME =      1.00
  YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .100000E+01   SO .00000
 TAO .126000E+02  TWB .114000E+02  TAI .159375E+02  G15 .418436E+00  G26 .00000
   Q .106159E-03   AQ .328770E+00
TIME =      2.00
  YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .200000E+01   SO .00000
 TAO .122000E+02  TWB .111000E+02  TAI .155343E+02  G15 .454499E+00  G26 .00000
   Q .115459E-03   AQ .727683E+00
TIME =      3.00
  YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .300000E+01   SO .00000
 TAO .116000E+02  TWB .106000E+02  TAI .159702E+02  G15 .591736E+00  G26 .00000
   Q .150126E-03   AQ .120574E+01
```

```
TIME =      4.00
   YR .780000E+02   MON .300000E+01   DAY .700000E+01    HR .400000E+01    SO .00000
  TAO .110000E+02   TWB .990000E+01   TAI .153564E+02   G15 .595461E+00   G26 .00000
    Q .151071E-03    AQ .174789E+01
TIME =      5.00
   YR .780000E+02   MON .300000E+01   DAY .700000E+01    HR .500000E+01    SO .00000
  TAO .106000E+02   TWB .940000E+01   TAI .156115E+02   G15 .671604E+00   G26 .00000
    Q .170388E-03    AQ .232651E+01
TIME =      6.00
   YR .780000E+02   MON .300000E+01   DAY .700000E+01    HR .600000E+01    SO .00000
  TAO .104000E+02   TWB .920000E+01   TAI .155273E+02   G15 .663457E+00   G26 .00000
    Q .168322E-03    AQ .293619E+01
TIME =      7.00
   YR .780000E+02   MON .300000E+01   DAY .700000E+01    HR .700000E+01    SO .50000
  TAO .104000E+02   TWB .910000E+01   TAI .153053E+02   G15 .594690E+00   G26 .00000
    Q .149911E-03    AQ .350901E+01
TIME =      8.00
   YR .780000E+02   MON .300000E+01   DAY .700000E+01    HR .800000E+01    SO .21800
  TAO .111000E+02   TWB .940000E+01   TAI .156075E+02   G15 .528907E-01   G26 .00000
    Q .134186E-04    AQ .380301E+01
TIME =      9.00
   YR .780000E+02   MON .300000E+01   DAY .700000E+01    HR .900000E+01    SO .44900
  TAO .128000E+02   TWB .104000E+02   TAI .212402E+02   G15 .000000E+00   G26 .00000
    Q .000000E+00    AQ .382716E+01
TIME =     10.00
   YR .780000E+02   MON .300000E+01   DAY .700000E+01    HR .100000E+02    SO .64100
  TAO .152000E+02   TWB .117000E+02   TAI .265007E+02   G15 .000000E+00   G26 .84379
    Q .375022E-06    AQ .382783E+01
TIME =     11.00
   YR .780000E+02   MON .300000E+01   DAY .700000E+01    HR .110000E+02    SO .77800
  TAO .172000E+02   TWB .128000E+02   TAI .265001E+02   G15 .000000E+00   G26 .46719
    Q .207641E-05    AQ .383225E+01
TIME =     12.00
   YR .780000E+02   MON .300000E+01   DAY .700000E+01    HR .120000E+02    SO .84900
  TAO .188000E+02   TWB .134000E+02   TAI .265050E+02   G15 .000000E+00   G26 .74737
    Q .332166E-05    AQ .384196E+01
TIME =     13.00
   YR .780000E+02   MON .300000E+01   DAY .700000E+01    HR .130000E+02    SO .85100
  TAO .201000E+02   TWB .137000E+02   TAI .265000E+02   G15 .000000E+00   G26 .89049
    Q .395777E-05    AQ .385507E+01
TIME =     14.00
   YR .780000E+02   MON .300000E+01   DAY .700000E+01    HR .140000E+02    SO .78300
  TAO .211000E+02   TWB .139000E+02   TAI .265003E+02   G15 .000000E+00   G26 .88013
    Q .391169E-05    AQ .386923E+01
TIME =     15.00
   YR .780000E+02   MON .300000E+01   DAY .700000E+01    HR .150000E+02    SO .65000
  TAO .221000E+02   TWB .141000E+02   TAI .265374E+02   G15 .000000E+00   G26 .74490
    Q .331069E-05    AQ .388223E+01
TIME =     16.00
   YR .780000E+02   MON .300000E+01   DAY .700000E+01    HR .160000E+02    SO .46100
  TAO .228000E+02   TWB .141000E+02   TAI .265052E+02   G15 .000000E+00   G26 .44261
    Q .196718E-05    AQ .389173E+01
TIME =     17.00
   YR .780000E+02   MON .300000E+01   DAY .700000E+01    HR .170000E+02    SO .23200
```

```
 TAO .228000E+02  TWB .139000E+02  TAI .260551E+02  G15 .000000E+00  G26 .00000
   Q .000000E+00   AQ .389527E+01
TIME =    18.00
  YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .180000E+02   SO .10000
 TAO .215000E+02  TWB .131000E+02  TAI .214884E+02  G15 .000000E+00  G26 .00000
   Q .000000E+00   AQ .389527E+01
TIME =    19.00
  YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .190000E+02   SO .00000
 TAO .193000E+02  TWB .119000E+02  TAI .191559E+02  G15 .000000E+00  G26 .00000
   Q .000000E+00   AQ .389527E+01
TIME =    20.00
  YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .200000E+02   SO .00000
 TAO .178000E+02  TWB .111000E+02  TAI .176747E+02  G15 .000000E+00  G26 .00000
   Q .000000E+00   AQ .389527E+01
TIME =    21.00
  YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .210000E+02   SO .00000
 TAO .174000E+02  TWB .111000E+02  TAI .172824E+02  G15 .000000E+00  G26 .00000
   Q .000000E+00   AQ .389527E+01
TIME =    22.00
  YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .220000E+02   SO .00000
 TAO .176000E+02  TWB .115000E+02  TAI .174840E+02  G15 .000000E+00  G26 .00000
   Q .000000E+00   AQ .389527E+01
TIME =    23.00
  YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .230000E+02   SO .00000
 TAO .172000E+02  TWB .117000E+02  TAI .170934E+02  G15 .000000E+00  G26 .00000
   Q .000000E+00   AQ .389527E+01
TIME =    24.00
  YR .780000E+02  MON .300000E+01  DAY .800000E+01   HR .000000E+00   SO .00000
 TAO .158000E+02  TWB .114000E+02  TAI .157132E+02  G15 .000000E+00  G26 .00000
   Q .000000E+00   AQ .389527E+01
```

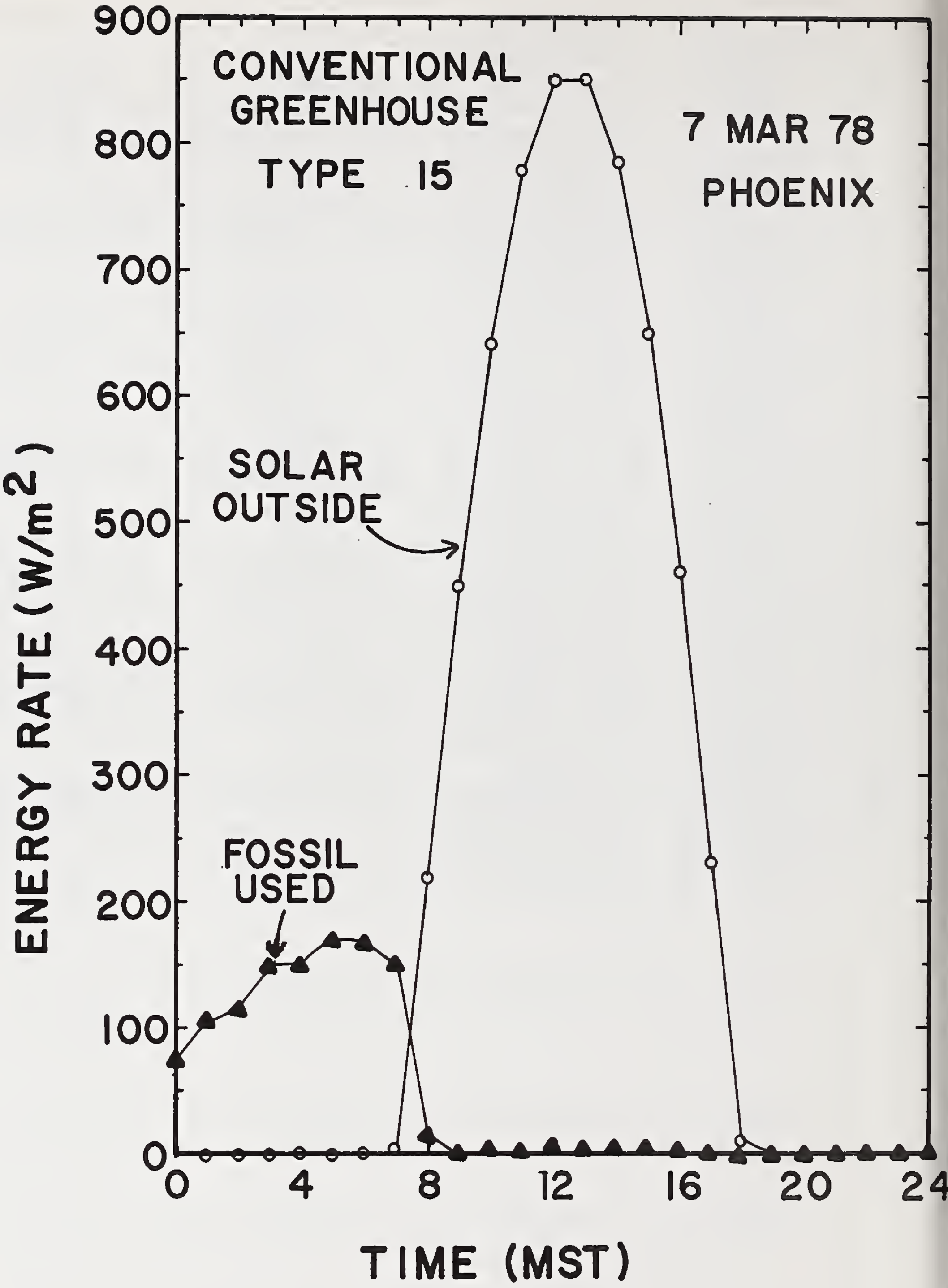

Figure 27.
Predicted fossil energy use rate versus time of day for simple conventional greenhouse example. Also, the solar radiation received outdoors on a horizontal surface.

Solar Greenhouse System

Figure 28 illustrates a solar greenhouse system that utilizes a tank of water in which to store energy for use at night. The system includes a direct-contact water-to-air heat exchanger for adding heat to the greenhouse at night and for removing excess heat from the greenhouse during the day. The removal of excess heat during the day cools the greenhouse while allowing the greenhouse to be unventilated and enriched with CO_2 for more sunlit hours than in a conventional greenhouse. The greenhouse is also equipped with dampers so that outside air can be drawn into the greenhouse through the heat exchanger (making it an evaporative cooler) if necessary in hot, humid weather. Figure 28 also shows a cooling tower for dumping excess energy in summer. This example is included to illustrate the versatility and power of MEB to handle a large system with several devices and complicated control logic.

Figure 29 shows an information flow diagram for the solar greenhouse system in figure 28, and figures 30 through 36 show the corresponding MEBDI file for defining and connecting the system. Referring to figure 30, the first lines and the first two units are essentially the same as for the previous (simple greenhouse) example, except that the type 13 reservoir additionally supplies values of 1.0 and 0.3 for the height and width of the vegetation rows to the type 14 greenhouse.

Unit 3 is a calendar (type 12 time function) which is included in the system to allow summer and winter modes of operation. In winter, solar energy collection from the greenhouse is to start at a lower temperature (24°C), and the cooling tower is "manually" turned completely off. In summer, solar energy collection (cooling) starts at a higher temperature (26.5°C), and the cooling tower is set to operate whenever the temperature of the water in the tank exceeds the outside wet bulb temperature by more than 2°C. For this example, however, the simulation is done for only a single winter day (7 March 1978). The parameters for the calendar are chosen so that the output from this unit is zero, to signal winter mode to the other devices.

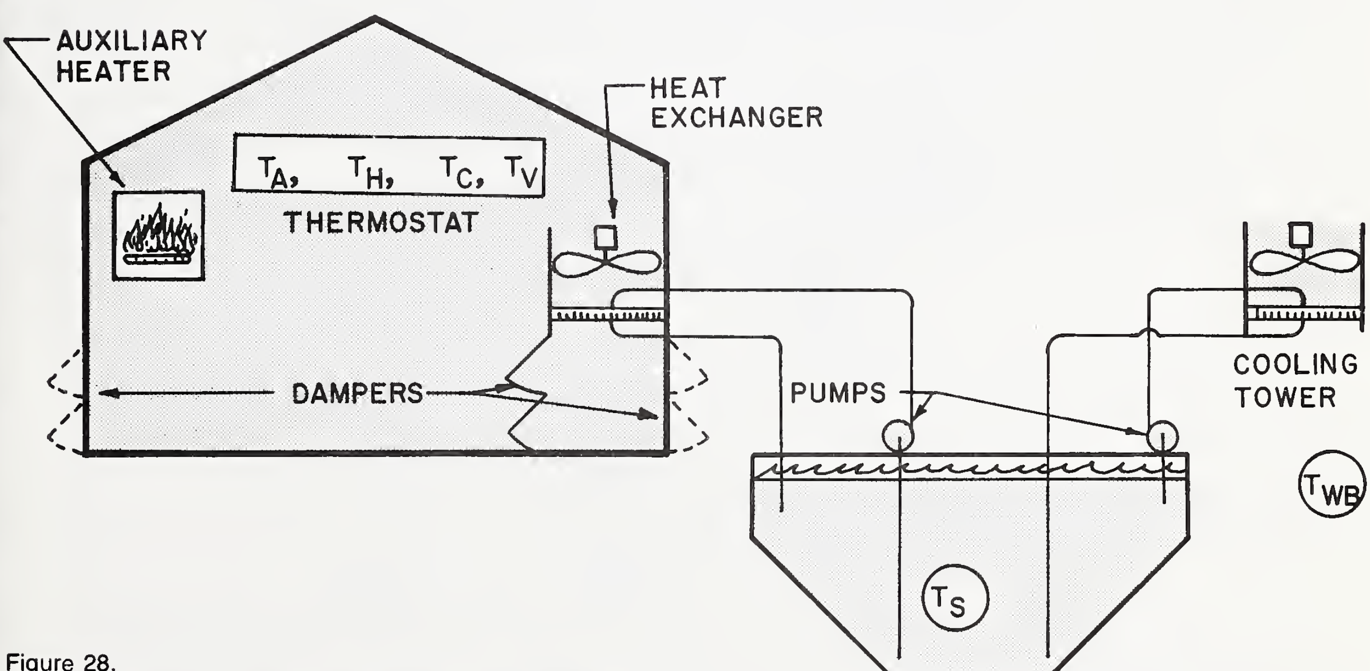

Figure 28.
Schematic diagram of an "unventilated" greenhouse with a solar energy storage water tank. A fossil fuel heater provides auxiliary heating, and a cooling tower provides additional cooling.

Unit 4 is a type 14 complicated greenhouse, whose characteristics are coded on the form in figure 31. The parameters are chosen to define a small fiberglass greenhouse (appendix E and table 1) similar in construction to the one used for the previous example. The greenhouse is connected to two external devices that can add energy to the greenhouse air: the type 16 heater (unit 9) and the type 13 heat exchanger (unit 13). The type 14 complicated greenhouse uses conduction transfer functions to predict soil heat flux, and these functions must be supplied in file MEBDI immediately following the initial values for the greenhouse. The functions for this example are coded on the form in figure 32, and they define a 30-cm-thick slab of moist sand over a dry loam (appendix E, Kimball *1983*).

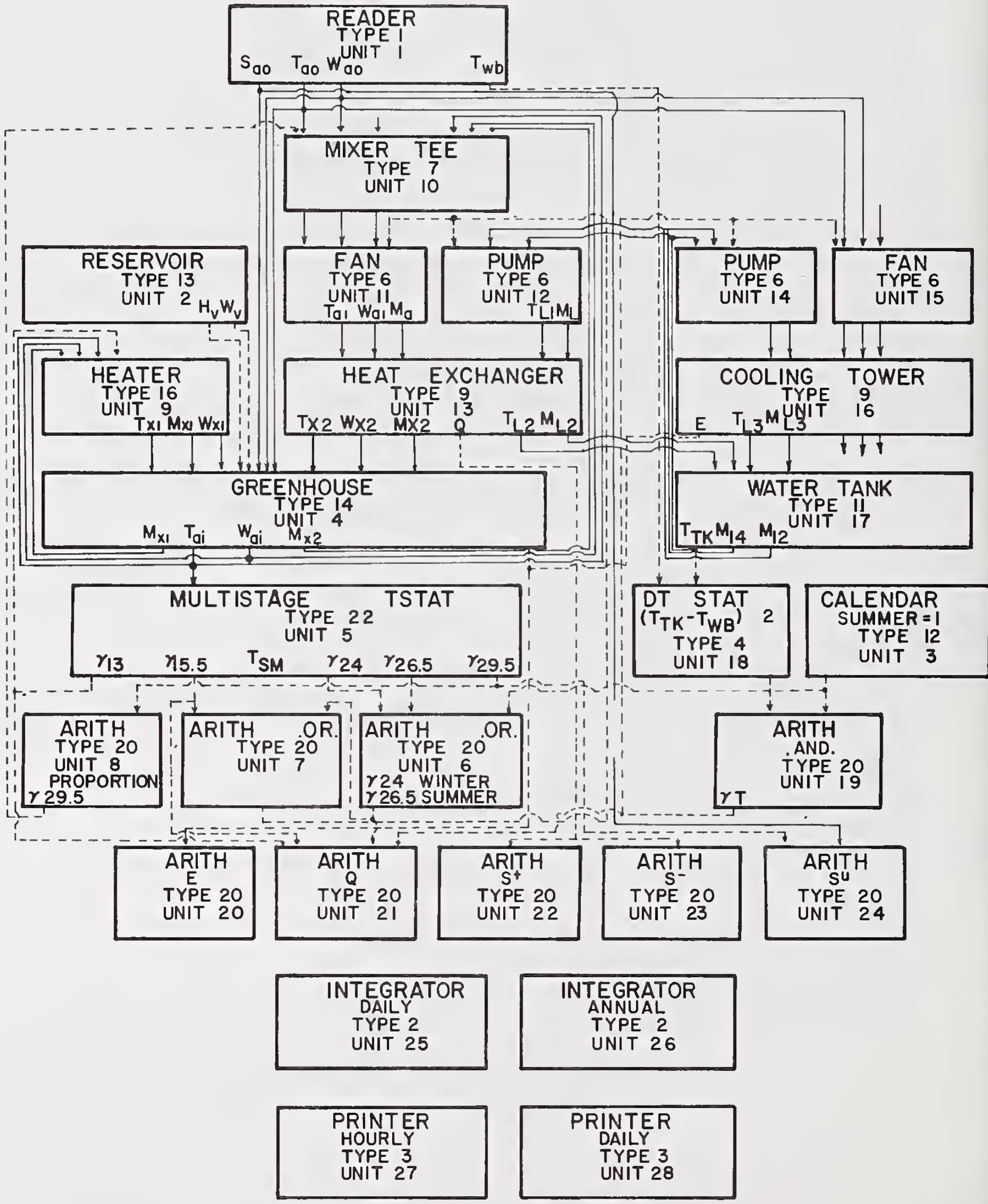

Figure 29.
Information flow diagram for the greenhouse of figure 28 with a solar energy storage water tank, auxiliary heater, and cooling tower.

Unit 5 in figure 29 and 30 is a type 22 multistage thermostat. The five set points are 13°, 15.5°, 24°, 26.5°, and 29.5°C for auxiliary heat, solar heating, solar collection in winter, solar collection in summer, and ventilation, respectively.

Units 6 and 7 illustrate the use of the type 20 arithmetic calculator to perform logic functions. Unit 6 selects the control variable corresponding to the 24°C set point in winter and the 26.5°C set point in summer. Unit 7 provides the control variable for the heat exchanger pump and fan and turns them on when the greenhouse temperature is below the 15.5°C thermostat set point or above the solar collection set point (24°C in winter or 26.5°C in summer, as chosen by unit 6).

Unit 8 modifies the 29.5°C ventilation control variable in a manner that forces the type 7 tee (unit 10) to simulate the action of the dampers of the actual test greenhouse at the USWCL. When the dampers open on the actual greenhouse, the fan no longer just recirculates greenhouse air but pulls in outside air. The proportion of outside air was measured to be 0.4 when the dampers were fully open; so unit 8 multiplies the 29.5°C control variable from the thermostat by 0.4 so that the unit 10 mixer will mix 0.4 outside air with 0.6 greenhouse air when the greenhouse air temperature exceeds 29.5°C.

Unit 9 is the auxiliary fossil fuel heater similar to the one that was the only heater in the previous example. Units 11, 12, and 13 comprise the solar heating and collection devices for transferring heat from the water tank to the greenhouse when the greenhouse temperature is below 15.5°C and for transferring solar energy from the greenhouse to the tank when the greenhouse temperature exceeds 24°C in winter or 26.5°C in summer. The parameters for the type 9 heat exchanger define a direct-contact, counterflow exchanger with excelsior pad media (appendix E, Kimball et al. *1977*).

Units 14, 15, and 16 are the pump, fan, and cooling tower. The parameters for the cooling tower actually define it as a direct-contact, counterflow heat exchanger like the one inside the greenhouse, except that the cooling tower uses dry outside air for evaporative cooling whereas humid greenhouse air is recirculated through the inside heat exchanger. The pump and fan are controlled by unit 19, which is a type 20 arithmetic calculator used to combine the signals from a type 4 differential thermostat (unit 18) and the calendar (unit 3). The water tank temperature must exceed the outside dry bulb temperature by more than 2°C *and* the calendar must indicate summer mode before the pump and fan are turned on.

The main component of the solar energy system in figure 28 is the solar energy storage water tank, which is unit 17 in figures 29 and 34. The tank is a very large cylinder, 1.5 m high by 7.32 m in diameter, with a capacity of 63 m^3, and it provides 2.3 m^3 of water per square meter of greenhouse. Thermal stratification is ignored, and the tank is assumed to be well mixed, so there is only one layer. This device is the only one in the whole system which has a differential equation. In this case, the dependent variable is the tank water temperature; and based on previous operating experience and simulation runs, it is set at 18.5°C.

Units 20 through 24 in figures 29 and 34 are type 20 arithmetic calculators for calculating some performance information from the system that involves manipulating the outputs from several devices. Again, the notation <*a,b*> will mean the value of output *b* from unit *a*. The constants used include 2.45E6 J/kg for converting latent

energy to mass, (1/27 m^2) (1 $m^3/10^3$ kg) (10^3 mm/m) = 1 mm/27 kg for converting kilograms per second for whole greenhouse to millimeters per second, and 1/27E6 for converting joules per second for whole greenhouse to megajoules per square meter per second.

Unit 20 computes the total water loss rate from the system, *E*, (mm/s). Ignoring leaks, the possible avenues of water loss are infiltration, natural ventilation, and fan ventilation from the greenhouse and evaporation from the cooling tower. Outputs 29 and 31 (<4,29> + <4,31>) from the greenhouse are the latent energy loss due to infiltration and natural ventilation, and output 7 (<16,7>) is the evaporation rate from the cooling tower. The rate of water loss from fan ventilation is the mass flow rate of the fan (kg/s) (<11,2>) times the fraction of outside air drawn in (<8,1>) times the difference in humidity ratio between the inside and outside air (<4,7> – <1,6>). Thus,

$$E = [(<4{,}29> + <4{,}31>)/2.45\text{E}6 + <16{,}7> \\ + <11{,}2> * <8{,}1> * (<4{,}7> - <1{,}6>)]/27.$$

Unit 21 computes the total fossil-energy-use rate, *Q* (MJ/s). The consumers of fossil energy in the system include the auxiliary heater, the fan and pump for the heat exchanger, and the fan and pump for the cooling tower. The energy use rates are the maximum capacities times their respective control variables. The heater capacity is 6,850 W, and the capacity of the fan plus pump for both heat exchanger and cooling tower is taken to be 1,800 W. Thus,

$$Q = [6{,}860 * <5{,}1> + 1{,}800 * <7{,}1> + 1{,}800 * <19{,}1>]/27.\text{E}6$$

Units 22 and 23 compute the rates of solar energy collection, S^+, and solar energy use, S^- (MJ/s). The collection rate is defined as the rate of energy transfer from the greenhouse air to the water, and the use rate is defined as rate from water to air. Therefore, the use rate consists of positive values from output 6 of the heat exchanger, and the collection rate consists of –1 times the negative values of this same output.

Unit 24 computes the amount of solar radiation, S^u, that is received outside while the greenhouse is closed or unventilated and therefore could be enriched with CO_2. The fraction of time the greenhouse is unventilated is 1 minus the control variable for ventilation, <5,10>, and 1 – <5,10> = <5,9>; therefore,

$$S^u = (<1{,}12> * <5{,}9>)/1.\text{E}6$$

Units 25 and 26 in figures 29 and 35 illustrate the use of type 2 integrators with different reset times. Both integrate the water and energy use variables; but unit 25 resets every 24 hours, whereas unit 26 continues to accumulate for a year.

Units 27 and 28 illustrate the use of type 3 printers with different printout times. Unit 27 prints out each hour, whereas unit 28 prints integrated values only at the end of each day. Table 3 explains the items and labels printed by both of the type 3 printers.

MODULAR ENERGY BALANCE MODEL INPUT DATA (MEBDI)

RUN TITLE: SOLAR GREENHOUSE SYSTEM EXAMPLE (7MAR78 DATA)

WEATHER FILE: P837

OUTPUT FILE: 6

YR(2)	STARTING TIME MON	DAY	HR(.)	TIME INCRE	NO. TIMES	FIRST TRACE	LAST TRACE

NO. UNITS: 28

UNIT 1 2 3 4 5 6 7 8 9 10 11 12 13 14

1
- TYPE: 1, READER
- PAR:
- IN:
- OUT: 1,1, 1,1, 1,1, 1,1, 1,1, 1,1, 1,1, 1,1, 1,1, 1,1, 1,1, 1,1, 1
- T:

2
- TYPE: 13, RESERVOIR
- PAR: 4/, 0.0, 0.8, 0.2,
- IN:
- OUT: 0.0, 0.8, 0.2,
- T:

3
- TYPE: 12, CALENDAR "0" FOR WINTER
- PAR: 5/, 0, 0, 193, 0,
- IN:
- OUT: 0, 1,
- T:

4
- TYPE: 14, GREENHOUSE - SEE ATTACHED FORMS (FIGS 31, 32)
- PAR:
- IN:
- OUT:
- T:

5
- TYPE: 22, MULTISTAGE THERMOSTAT
- PAR: 7/, 20, 13, 15.5, 24, 26.5, 29.5,
- IN: 4, 6,
- OUT: 0, 1, 0.5, 0.5, 1, 0, 1, 0, 1, 0,
- T:

6
- TYPE: 20, ARITH CHOOSE G24 IN WINTER OR G26.5 IN SUMMER
- PAR: 9/, 4, 0, 0, 10, 0, 0, 10, 9,
- IN: 5, 6, 3, 2, 5, 8, 3, 1,
- OUT: 0, 1,
- T:

7
- TYPE: 20, ARITH "1" IF TAI TOO COLD OR TOO HOT
- PAR: 5/, 2, 0, 0, 9,
- IN: 5, 3, 6, 1,
- OUT: 0.5, 0.5,
- T:

Figure 30.
Completed data form for units 1 through 7 of file MEBDI for solar greenhouse system example.

TYPE 14 COMPLICATED GREENHOUSE DATA

Unit No: 4

Parameters

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
J	A_c	A_g	v_{ai}	I	s	Ne	x_e	ρ_v	ρ_g	ϵ_v	ϵ_g	ϵ_c	C_{xc}	C_{xg}	C_{xe}
2	62	27	73	5	1.0	1	0	0.13	0.16	0.98	0.95	0	0	0	0
17	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**
b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9	b_{10}	r_g	h_{p1}	X_{RM}	f	τ_{sco0}	τ_{sco}
5.7	3.8	1.5	0.33	9.0	4.5	0	100	20300	17	100	6	0	0	0.66	0
33	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**
τ_{Sci}				α_{Sco}		α_{Sci}				U_c				τ_{Rco}	
00	01	10	11	0	1	00	01	10	11	00	01	10	11	0	1
1.00	0	0	0	0.24	0	0.00	0	0	0	160	0	0	0	0.07	0
49	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**
τ_{Rci}				ϵ_{coo}		ϵ_{coi}		ϵ_{cio}				ϵ_{cii}			
00	01	10	11	0	1	0	1	00	01	10	11	00	01	10	11
1.00	0	0	0	0.87	0	0.87	0	0.00	0	0	0	0.00	0	0	0
65	**66**	**67**	**68**	**69**	**70**	**71**	**72**	**73**	**74**	**75**	**76**				
b_{11}				b_{12}				b_{13}							
00	01	10	11	00	01	10	11	00	01	10	11				
0.12	0.12	0	0	0.039	0.039	0	0	0.00	0.23	0	0				

Inputs

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
S_o	R_{ao}	u_{ao}	P_{ao}	T_{ao}	W_{ao}	y	w
1 12	1 21	1 7	1 8	1 9	1 6	2 2	2 3
9	**10**	**11**	**12**	**13**	**14**	**15**	**16**
γ_f	γ_{co}	γ_{ci}	γ_p	γ_N	γ_e	γ_R	T_{xc}
2 1	2 1	2 1	8 2	2 1	2 1	2 1	2 1
17	**18**	**19**	**20**	**21**	**22**	**23**	**24**
M_{xc}	T_{xg}	M_{xg}	T_{xe}	M_{xe}	T_{x1}	M_{x1}	W_{x1}
2 1	2 1	2 1	2 1	2 1	9 1	9 2	9 3
25	**26**	**27**	**28**	**29**	**30**		
T_{x2}	M_{x2}	W_{x2}	T_{x3}	M_{x3}	W_{x3}		
13 1	13 2	13 3					

Initial Output Guesses

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
T_{co}	T_{ci}	T_v	T_{go}	T_e	T_{ai}	W_{ai}	T_{gs}	44
13	13	15.5	18	-2	15.5	0.01	21.6	1's

9 through **46+3*J** are usually all 1's separated by comma-blank

Continue on form for surface layer soil heat conduction transfer functions

Figure 31.
Completed data form for type 14 complicated greenhouse of file MEBDI for solar greenhouse system example.

TYPE 14 COMPLICATED GREENHOUSE DATA—Continued

Soil Heat Conduction Transfer Functions and Temperature History

M	$G_{O,to-1}$	$G_{so,to-1}$	Upper Slab Description
11	-500	-500	30-cm-thick slab of moist sand
B_r	**T_d**	**B_{41}**	**Lower Semi-infinite Description**
0.72749	18	17.34	Avondale loam @ 0.1 m^3/m^3 H_2O

m	B_{1m}	B_{2m}	B_{3m}	$T_{go,to-m+1}$	$T_{gs,to-m+1}$	Time*
1	39.3336	0.0018	46.6613	— —	— —	— —
2	-51.3176	0.2246	-61.4591	19.1	21.7	23
3	12.7625	0.7904	15.3308	19.6	21.7	22
4	0.7981	0.5485	0.9750	20.1	21.8	21
5	0.1899	0.1931	0.2388	20.9	21.7	20
6	0.0526	0.0580	0.0666	22.1	21.6	19
7	0.0151	0.0169	0.0191	23.7	21.3	18
8	0.0043	0.0049	0.0055	26.1	21.0	17
9	0.0013	0.0014	0.0016	27.8	20.7	16
10	0.0004	0.0004	0.0005	28.8	20.4	15
11	0.0001	0.0001	0.0001	28.9	20.1	14
12						
13						
14						
15						
16						
17						
18						
19						
20						
21						
22						
23						
24						

*Not used

Figure 32.
Completed data form with soil conduction transfer functions for type 14 complicated greenhouse of file MEBDI for solar greenhouse system example.

MEB MODEL INPUT DATA - CONTINUED

UNIT	Field	Entries
8	TYPE:	20, ARITH PROPORTION DAMPER SO OPEN GIVES 0.4 OUTSIDE AIR
	PAR:	6, 1, 0, -1, 0.4, 1
	IN:	5, 10
	OUT:	0, 1
	T:	
9	TYPE:	16, HEATER
	PAR:	6850, 0.26, 0.0
	IN:	4, 6, 9, 2, 4, 7, 5, 1
	OUT:	20, 0, 0
	T:	
10	TYPE:	7, TEE MIX 0.4 OUTSIDE AIR WITH GREENHOUSE AIR
	PAR:	3
	IN:	1, 9, 4, 51, 1, 6, 4, 6, 4, 51, 4, 7, 8, 1
	OUT:	15, 0.0, 0.01, 0, 1.8, 0
	T:	
11	TYPE:	6, Greenhouse FAN
	PAR:	3.7
	IN:	10, 1, 10, 2, 10, 3, 7, 1
	OUT:	15, 1.8, 0.01
	T:	
12	TYPE:	6, Greenhouse Pump
	PAR:	3.7
	IN:	17, 1, 17, 2, 17, 3, 7, 1
	OUT:	18.5, 1.8, 0
	T:	
13	TYPE:	9, HEAT EXCHANGER (EXCELSIOR PADS)
	PAR:	1, -1, 4.6, 0.051, 4190, 37, 1.46, 0.10, 65000, 0.4, 0.83, 0
	IN:	11, 1, 11, 2, 11, 3, 12, 1, 12, 2, 1, 8, 13, 4, 7, 1
	OUT:	15.5, 1.8, 0.01, 15.5, 1.8, 0, 0
	T:	
14	TYPE:	6, COOLING TOWER PUMP
	PAR:	3.7
	IN:	17, 3, 17, 4, 2, 1, 19, 1
	OUT:	18.5, 0, 0
	T:	
15	TYPE:	6, COOLING TOWER FAN
	PAR:	3.7
	IN:	1, 9, 15, 2, 1, 6, 19, 1
	OUT:	16, 0, 0
	T:	
16	TYPE:	9, COOLING TOWER (EXCELSIOR PADS)
	PAR:	1, -1, 4.6, 0.051, 4190, 37, 1.46, 0.10, 65000, 0.4, 0.83, 0
	IN:	15, 1, 15, 2, 15, 3, 14, 1, 14, 2, 1, 8, 16, 4, 19, 1
	OUT:	16, 0, 0, 16, 0, 0, 0
	T:	

PRINTER: b---b---b---b---b---b---b---b---b---b---b---b---b---b---

LABELS: b---b---b---b---b---b---b---b---b---b---b---b---b---b---

Figure 33.
Completed data form for units 8 through 16 of file MEBDI for solar greenhouse system example.

MEB MODEL INPUT DATA - CONTINUED

Unit	Field	Entries (columns 1–14)
17	TYPE:	11, WATER TANK (1.5 M HIGH x 7.32 M DIA.)
	PAR:	1, 63, 1.5, 4190, 1000, 0.1, 18.5, 0, 1, 1, 0, 0
	IN:	13, 4, 13, 5, 16, 4, 16, 5, 1, 9, 2, 1
	OUT:	18.5, 1.8, 18.5, 0, 0, 0, 0, 0
	T:	18.5
18	TYPE:	4, DIFFERENTIAL THERMOSTAT (OUTPUT 2 ON IF TTK-TWB>2)
	PAR:	2, 18, 2
	IN:	17, 3, 1, 10
	OUT:	1, 0
	T:	
19	TYPE:	20, ARITH TOWER LOGIC ('1' IF SUMMER AND HAVE WARM TANK)
	PAR:	5/, 2, 0, 0, 10
	IN:	3, 1, 18, 2
	OUT:	0, 1
	T:	
20	TYPE:	20, ARITH TOTAL WATER LOSS RATE OF GREENHOUSE + TOWER (mm/s)
	PAR:	21/, 7, 0, 0, 3, -1, 2.45E6, 2, 0, 3, 0, 0, 1, 0
	IN:	4, 29, 4, 31, 16, 7, 11, 2, 8, 1, 4, 7, 1, 6
	OUT:	0, 1
	T:	
	TYPE:	CONTINUE
	PAR:	0, 4, 1, 3, -1, 27, 2
	IN:	
	OUT:	
	T:	
21	TYPE:	20, ARITH TOTAL FOSSIL ENERGY USE RATE (MJ/S/M2)
	PAR:	16/, 3, 0, -1, 6850, 1, 0, 0, 3, -1, 1800, 1, 3, -1, 27.E6, 2
	IN:	5, 1, 7, 1, 19, 1
	OUT:	0, 1
	T:	
22	TYPE:	20, ARITH SOLAR ENERGY COLLECTION RATE (MJ/S/M2)
	PAR:	8/, 1, 0, 7, 8, -1, 27.E6, 2
	IN:	13, 6
	OUT:	0, 1
	T:	
23	TYPE:	20, ARITH SOLAR ENERGY USE RATE (MJ/S/M2)
	PAR:	7/, 1, 0, 8, -1, 27.E6, 2
	IN:	13, 6
	OUT:	0, 1
	T:	
24	TYPE:	20, ARITH SOLAR RECEIVED WHILE UNVENTILATED (MJ/S/M2)
	PAR:	8/, 2, 0, 0, 1, -1, 1.E6, 2
	IN:	1, 12, 5, 9
	OUT:	0, 1
	T:	

PRINTER: b---b---b---b---b---b---b---b---b---b---b---b---b---b---
LABELS: b---b---b---b---b---b---b---b---b---b---b---b---b---b---

Figure 34.
Completed data form for units 17 through 24 of file MEBDI for solar greenhouse system example.

MEB MODEL INPUT DATA - CONTINUED

UNIT		1 2 3 4 5 6 7 8 9 10 11. 12 13 14
25	TYPE:	2, DAILY INTEGRATOR
	PAR:	6, 24, 25,
	IN:	1, 12, 20, 1, 21, 1, 22, 1, 23, 1, 24, 1,
	OUT:	0, 0, 0, 0, 0, 0
	T:	
26	TYPE:	2, ANNUAL INTEGRATOR
	PAR:	6, 8761, 26,
	IN:	1, 12, 20, 1, 21, 1, 22, 1, 23, 1, 24, 1,
	OUT:	0, 0, 0, 0, 0, 0
	T:	
27	TYPE:	3, HOURLY PRINTER
	PAR:	34, 1, 80, 27,
	IN:	1, 1, 1, 2, 1, 3, 1, 4, 1, 12, 1, 9, 1, 6, 4, 1, 4, 2, 4, 3, 4, 4, 4, 6, 4, 7, 4, 8
	LABELS ~~OUT~~:	YR, MON, DAY, HR, SO, TAO, WAO, TCO, TCI, TV, TG, TAI, WAI, TGS
	T:	
		CONTINUE
	TYPE:	
	PAR:	
	IN:	17, 1, 13, 1, 13, 2, 13, 3, 13, 4, 13, 5, 16, 4, 16, 5, 5, 1, 5, 3, 5, 6, 5, 8, 5, 10, 7, 1
	LABELS ~~OUT~~:	TTK, TAX, MAX, WAX, TLX, MLX, TLT, MLT, G13, G15, G24, G26, G29, GX
	T:	REMEMBER, PRINT LABELS FOLLOW INPUTS
		CONTINUE
	TYPE:	
	PAR:	
	IN:	19, 1, 20, 1, 21, 1, 22, 1, 23, 1, 24, 1,
	LABELS ~~OUT~~:	GCT, E, Q, S+, S-, SU,
	T:	
28	TYPE:	3, DAILY PRINTER
	PAR:	12, 24, 80, 28,
	IN:	25, 1, 25, 2, 25, 3, 25, 4, 25, 5, 25, 6, 26, 1, 26, 2, 26, 3, 26, 4, 26, 5, 26, 6,
	OUT:	
	T:	
	TYPE:	
	PAR:	
	IN:	
	OUT:	
	T:	
	TYPE:	
	PAR:	
	IN:	
	OUT:	
	T:	
	TYPE:	
	PAR:	
	IN:	
	OUT:	
	T:	

PRINTER: b– DS b– DE b– DQ b DS+ b DS- b DSU b– AS b– AE b– AQ b AS+ b AS- b ASU b– – –b– – –
LABELS: b– – –b– – –b– – –b– – –b– – –b– – –b– – –b– – –b– – –b– – –b– – –b– – –b– – –b– – –b– – –

Figure 35.
Completed data form for units 25 through 28 of file MEBDI for solar greenhouse system example.

Table 3.— Detailed explanation of printer labels for solar greenhouse system example

Printer input No.	Label	Item	From— Unit No.	Output No.
Hourly printer:				
1	YR	year	1	1
2	MON	month	1	2
3	DAY	day	1	3
4	HR	hour	1	4
5	SO	outside solar radiation (W/m^2)	1	12
6	TAO	outside air temperature (°C)	1	9
7	WAO	outside humidity ratio (kg/kg)	1	6
8	TCO	greenhouse outside cover temperature (°C)	4	1
9	TCI	greenhouse inside cover temperature (°C)	4	2
10	TV	greenhouse vegetation temperature (°C)	4	3
11	TG	greenhouse soil surface temperature (°C)	4	4
12	TAI	greenhouse air temperature (°C)	4	6
13	WAI	greenhouse humidity ratio (kg/kg)	4	7
14	TGS	greenhouse soil storage temperature (°C)	4	8
15	TTK	water temperature in tank (°C)	17	1
16	TAX	air temperature from heat exchanger (°C)	13	1
17	MAX	air flow rate from heat exchanger (kg/s)	13	2
18	WAX	air humidity ratio from heat exchanger (kg/kg)	13	3
19	TLX	water temperature from heat exchanger (°C)	13	4
20	MLX	water flow rate from heat exchanger (kg/s)	13	5
21	TLT	water temperature from cooling tower (°C)	16	4
22	MLT	water flow rate from cooling tower (kg/s)	16	5
23	G13	control variable @ 13°C	5	1
24	G15	control variable @ 15.5°C	5	3
25	G24	control variable @ 24.5°C	5	6
26	G26	control variable @ 26.5°C	5	8
27	G29	control variable @ 29.5°C	5	10
28	GX	control variable for heat exchanger fan and pump	7	1
29	GCT	control variable for cooling tower fan and pump	19	1
30	E	water loss rate (mm/s)	20	1
31	Q	fossil energy use rate ($MJ/m^2 \cdot s$)	21	1
32	S+	solar energy collection rate ($MJ/m^2 \cdot s$)	22	1
33	S−	solar energy use rate ($MJ/m^2 \cdot s$)	23	1
34	SU	solar radiation received while unventilated ($MJ/m^2 \cdot s$)	24	1

Table 3.— Detailed explanation of printer labels for solar greenhouse system example—Continued

Printer input No.	Label	Item	From— Unit No.	Output No.
Daily printer:				
1	DS	daily outside solar radiation (J/m^2)	25	1
2	DE	daily water loss (mm)	25	2
3	DQ	daily fossil energy use (MJ/m^2)	25	3
4	DS+	daily solar energy collected (MJ/m^2)	25	4
5	DS−	daily solar energy used (MJ/m^2)	25	5
6	DSU	daily solar radiation received while unventilated (MJ/m^2)	25	6
7	AS	accum.[1] outside solar radiation (J/m^2)	26	1
8	AE	accum.[1] water loss (mm)	26	2
9	AQ	accum.[1] fossil energy use (MJ/m^2)	26	3
10	AS+	accum.[1] solar energy collected (MJ/m^2)	26	4
11	AS−	accum.[1] solar energy used (MJ/m^2)	26	5
12	ASU	accum.[1] solar radiation received while unventilated (MJ/m^2	26	6

[1]accumulated from start of simulation.

Figure 36 is a listing of file MEBDI that was entered into the computer from the forms in figures 30 through 35. Then figure 37 is the sample printout from a run with the solar greenhouse example. As usual, the first portion is a printout of information read from the MEBDI file, and the user is again cautioned to check his or her own printouts carefully for possible misconnections or other errors. Next in the printout is the hour-by-hour listing of the many system variables as specified in figure 35 and table 3. Note the several FOG ENCOUNTERED IN LXCHNR messages. These warn that at night the air in the type 9 direct-contact latent and sensible heat exchanger became saturated—a condition that, in this case, is not surprising or consequential. Finally, at the end of figure 37, there is a daily summary of the integrated variables from the daily printer. The variables whose labels start with D are daily totals, whereas those whose labels start with A are total accumulations since the start of the simulation (table 3). Because this example was only run for 1 day, the corresponding D and A values are equal.

The hourly solar radiation, fossil energy used, solar energy collected, and solar energy used are plotted against time of day in figure 38 for the solar greenhouse system example. Comparison with figure 27 for the conventional greenhouse shows that the solar greenhouse required only about one-third as much fossil energy. The energy used by the solar greenhouse was solely electrical, however, since no auxiliary heat was required (figure 37), and electrical energy costs considerably more than other energy sources that could be burned in the conventional greenhouse. Therefore, the parasitic consumption of electrical energy by the fans and pumps in this solar system example significantly decreases the advantage of the solar greenhouse over the conventional greenhouse. Regardless, however, of the practical significance of the difference in energy consumption between these two greenhouses, these examples serve to demonstrate the power and versatility of the MEB model for simulating a variety of systems with few or many devices and simple or complex control strategies.

Figure 36.
Listing of file MEBDI for the solar greenhouse system example.

```
SOLAR GREENHOUSE SYSTEM EXAMPLE (7MAR78 DATA)    FILE ISGSX
P837
6
78,  3,  7, 0.0, 1.0,25,  0,0
28
1, READER                                                   UNIT 1
1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1
13, RESERVOIR                                               UNIT 2
4
0.0, 0.8, 0.2
0.0, 0.8, 0.2
12, CALENDAR      "0" FOR WINTER                            UNIT 3
5
0,0,193,0
0,1
14, COMPLICATED GREENHOUSE                                  UNIT 4
2, 62, 27, 73, 5, 1.0, 1, 0, 0.13, 0.16, 0.98, 0.95, 0, 0, 0, 0/
5.7, 3.8, 1.5, 0.33, 9.0, 4.5, 0, 100, 20300, 17, 100, 6, 0, 0, 0.66, 0/
1.00, 0, 0, 0, 0.24, 0, 0.00, 0, 0, 0, 160, 0, 0, 0, 0.07, 0/
1.00, 0, 0, 0, 0.87, 0, 0.87, 0, 0.00, 0, 0, 0, 0.00, 0, 0, 0/
0.12, 0.12, 0, 0, 0.039, 0.039, 0, 0, 0.00, 0.23, 0, 0
1,12, 1,21, 1,7, 1,8, 1,9, 1,6, 2,2, 2,3/
2,1, 2,1, 2,1, 8,2, 2,1, 2,1, 2,1, 2,1/
2,1, 2,1, 2,1, 2,1, 2,1, 9,1, 9,2, 9,3/
13,1, 13,2, 13,3
13, 13, 15.5, 18, -2, 15.5 0.01, 21.6, 1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1/
1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1
11, -500, -500, 30-CM-THICK SLAB OF MOIST SAND
0.72749, 18, 17.34, AVONDALE LOAM @ 0.10 M3 H2O/M3 SOIL
1,  39.3336, 0.0018,  46.6613
2, -51.3176, 0.2246, -61.4591, 19.1, 21.7
3,  12.7625, 0.7904,  15.3308, 19.6, 21.7
4,    0.7981, 0.5485,   0.9750, 20.1, 21.8
5,    0.1899, 0.1931,   0.2388, 20.9, 21.7
6,    0.0526, 0.0580,   0.0666, 22.1, 21.6
7,    0.0151, 0.0169,   0.0191, 23.7, 21.3
8,    0.0043, 0.0049,   0.0055, 26.1, 21.0
9,    0.0013, 0.0014,   0.0016, 27.8, 20.7
10,   0.0004, 0.0004,   0.0005, 28.8, 20.4
11,   0.0001, 0.0001,   0.0001, 28.9, 20.1
22, MULTISTAGE THERMOSTAT                                   UNIT 5
7
20, 13, 15.5, 24, 26.5, 29.5
4,6
0, 1, .5,.5,  1, 0,  1, 0,  1, 0
20, ARITH CHOOSE G24 IN WINTER OR G26.5 IN SUMMER           UNIT 6
9
4, 0, 0, 10, 0, 0, 10, 9
5,6, 3,2, 5,8, 3,1
0,1
20, ARITH  '1' IF TAI TOO COLD OR TOO HOT                   UNIT 7
5
2, 0, 0, 9
```

```
5,3, 6,1
.5,.5
20, ARITH PROPORTION DAMPER SO OPEN GIVES .4 OUTSIDE AIR        UNIT 8
6
1, 0, -1, 0.4, 1
5, 10
0,1
16, HEATER                                                      UNIT 9
6850, 0.26, 0.0
4,6, 9,2, 4,7, 5,1
20, 0, 0
7, TEE MIX 0.4 OUTSIDE AIR WITH GREENHOUSE AIR                  UNIT 10
3
1,9, 4,51, 1,6, 4,6, 4,51, 4,7, 8,1
15, 0.0, 0.01, 0, 1.8, 0
6, GREENHOUSE FAN                                               UNIT 11
3.7
10,1, 10,2, 10,3, 7,1
15, 1.8, 0.01
6, GREENHOUSE PUMP                                              UNIT 12
3.7
17,1, 17,2, 2,1, 7,1
18.5, 1.8, 0
9, HEAT EXCHANGER (EXCELSIOR PADS)                              UNIT 13
1, -1, 4.6, 0.051, 4190, 37, 1.46, 0.10, 65000, 0.4, 0.83, 0
11,1, 11,2, 11,3, 12,1, 12,2, 1,8, 13,4, 7,1
15.5, 1.8, 0.01, 15.5, 1.8, 0, 0
6, COOLING TOWER PUMP                                           UNIT 14
3.7
17,3, 17,4, 2,1, 19,1
18.5, 0, 0
6, COOLING TOWER FAN                                            UNIT 15
3.7
1,9, 15,2, 1,6, 19,1
16, 0, 0
9, COOLING TOWER (EXCELSIOR PADS)                               UNIT 16
1, -1, 4.6, 0.051, 4190, 37, 1.46, 0.10, 65000, 0.4, 0.83, 0
15,1, 15,2, 15,3, 14,1, 14,2, 1,8, 16,4, 19,1, 19,1
16, 0, 0, 16, 0, 0, 0
11, WATER TANK (1.5M HIGH BY 7.32M DIAMETER)                    UNIT 17
1, 63, 1.5, 4190, 1000, 0.1, 18.5, 0, 1, 1, 0, 0
13,4, 13,5, 16,4, 16,5, 1,9, 2,1
18.5, 1.8, 18.5, 0, 0, 0, 0, 0
18.5
4, DIFFERENTIAL THERMOSTAT (ON IF TTK-TWB > 2)                  UNIT 18
2, 18, 2
17,3, 1,10
1, 0
20, ARITH  TOWER LOGIC ('1' IF SUMMER AND HAVE WARM TANK)       UNIT 19
5
2, 0, 0, 10
3,1, 18,2
0,1
20, ARITH  TOTAL WATER LOSS RATE OF GREENOUSE + TOWER (MM/S)    UNIT 20
21
```

```
7, 0, 0, 3, -1, 2.45E6, 2, 0, 3, 0, 0, 1, 0, 0, 4/
1, 3, -1, 27, 2
4,29, 4,31, 16,7, 11,2, 8,1, 4,7, 1,6,
0, 1
20, ARITH TOTAL FOSSIL ENERGY USE RATE (MJ/S/M2)                UNIT 21
16
3, 0, -1, 6850, 1, 0, 0, 3, -1, 1800, 1, 3, -1, 27.E6, 2
5,1, 7,1, 19,1
0, 1
20, ARITH SOLAR ENERGY COLLECTION RATE (MJ/S/M2)                UNIT 22
8
1, 0, 7, 8, -1, 27.E6, 2
13,6
0, 1
20, ARITH SOLAR ENERGY USE RATE (MJ/S/M2)                       UNIT 23
7
1, 0, 8, -1, 27.E6, 2
13,6
0, 1
20, ARITH  SOLAR RECEIVED WHILE UNVENTILATED (MJ/S/M2)          UNIT 24
8
2, 0, 0, 1, -1, 1.E6, 2
1,12, 5,9
0,1
2, DAILY INTEGRATOR                                             UNIT 25
6, 24, 25
1,12, 20,1, 21,1, 22,1, 23,1, 24,1
0, 0, 0, 0, 0, 0
2, ANNUAL INTEGRATOR                                            UNIT 26
6, 8761, 26
1,12, 20,1, 21,1, 22,1, 23,1, 24,1
0, 0, 0, 0, 0, 0
3, HOURLY PRINTER                                               UNIT 27
34, 1, 80, 27
1,1, 1,2, 1,3, 1,4, 1,12, 1,9, 1,6, 4,1, 4,2, 4,3, 4,4, 4,6, 4,7, 4,8/
17,1, 13,1, 13,2, 13,3, 13,4, 13,5, 16,4, 16,5, 5,1, 5,3, 5,6, 5,8, 5,10, 7,1/
19,1, 20,1, 21,1, 22,1, 23,1, 24,1
  YR MON DAY  HR  SO TAO WAO TCO TCI  TV  TG TAI WAI TGS TTK TAX MAX WAX TLX MLX
 TLT MLT G13 G15 G24 G26 G29  GX GCT   E   Q  S+  S-  SU
3, DAILY PRINTER                                                UNIT 28
12, 24, 80, 28
25,1, 25,2, 25,3, 25,4, 25,5, 25,6, 26,1, 26,2, 26,3, 26,4, 26,5, 26,6
  DS  DE  DQ DS+ DS- DSU  AS  AE  AQ AS+ AS- ASU
```

Figure 37.
Sample printout for solar greenhouse system example.

```
                    MODULAR ENERGY BALANCE SIMULATION

SOLAR GREENHOUSE SYSTEM EXAMPLE (7MAR78 DATA)    FILE ISGSX
RUN AT 10:33 AM  TUE., 30  NOV., 1982
WEATHER DATA FROM FILE P837

STARTING YR=78. MN= 3. DY= 7. HR=  0.00

INCREMENT   =     1.00 HOURS
NO. TIMES   =       25
FIRST TRACE=    -1.00 HOURS
LAST  TRACE=    -1.00 HOURS
NO. UNITS   =       28


UNIT  1 IS A TYPE  1 READER
PARAMETERS
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
INITIAL OUTPUTS
  1 .1000E+01  2 .1000E+01  3 .1000E+01  4 .1000E+01  5 .1000E+01  6 .1000E+01
  7 .1000E+01  8 .1000E+01  9 .1000E+01 10 .1000E+01 11 .1000E+01 12 .1000E+01
 13 .1000E+01 14 .1000E+01 15 .1000E+01 16 .1000E+01 17 .1000E+01 18 .1000E+01
 19 .1000E+01 20 .1000E+01 21 .1000E+01 22 .1000E+01 23 .1000E+01
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT  2 IS A TYPE 13 RESERVOIR
PARAMETERS
  1 .4000E+01  2 .0000E+00  3 .8000E+00  4 .2000E+00
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
INITIAL OUTPUTS
  1 .0000E+00  2 .8000E+00  3 .2000E+00
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT  3 IS A TYPE 12 TIME FUNCTION
PARAMETERS
  1 .5000E+01  2 .0000E+00  3 .0000E+00  4 .1930E+03  5 .0000E+00
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
INITIAL OUTPUTS
  1 .0000E+00  2 .1000E+01
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT  4 IS A TYPE 14 COMPLICATED GREENHOUSE
PARAMETERS
  1 .2000E+01  2 .6200E+02  3 .2700E+02  4 .7300E+02  5 .5000E+01  6 .1000E+01
  7 .1000E+01  8 .0000E+00  9 .1300E+00 10 .1600E+00 11 .9800E+00 12 .9500E+00
 13 .0000E+00 14 .0000E+00 15 .0000E+00 16 .0000E+00 17 .5700E+01 18 .3800E+01
 19 .1500E+01 20 .3300E+00 21 .9000E+01 22 .4500E+01 23 .0000E+00 24 .1000E+03
 25 .2030E+05 26 .1700E+02 27 .1000E+03 28 .6000E+01 29 .0000E+00 30 .0000E+00
 31 .6600E+00 32 .0000E+00 33 .1000E+01 34 .0000E+00 35 .0000E+00 36 .0000E+00
 37 .2400E+00 38 .0000E+00 39 .0000E+00 40 .0000E+00 41 .0000E+00 42 .0000E+00
 43 .1600E+03 44 .0000E+00 45 .0000E+00 46 .0000E+00 47 .7000E-01 48 .0000E+00
 49 .1000E+01 50 .0000E+00 51 .0000E+00 52 .0000E+00 53 .8700E+00 54 .0000E+00
 55 .8700E+00 56 .0000E+00 57 .0000E+00 58 .0000E+00 59 .0000E+00 60 .0000E+00
 61 .0000E+00 62 .0000E+00 63 .0000E+00 64 .0000E+00 65 .1200E+00 66 .1200E+00
```

```
 67 .0000E+00 68 .0000E+00 69 .3900E-01 70 .3900E-01 71 .0000E+00 72 .0000E+00
 73 .0000E+00 74 .2300E+00 75 .0000E+00 76 .0000E+00
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
     1   1 12      2   1 21      3   1  7      4   1  8      5   1  9      6   1  6
     7   2  2      8   2  3      9   2  1     10   2  1     11   2  1     12   8  2
    13   2  1     14   2  1     15   2  1     16   2  1     17   2  1     18   2  1
    19   2  1     20   2  1     21   2  1     22   9  1     23   9  2     24   9  3
    25  13  1     26  13  2     27  13  3
INITIAL OUTPUTS
  1 .1300E+02  2 .1300E+02  3 .1550E+02  4 .1800E+02  5-.2000E+01  6 .1550E+02
  7 .1000E-01  8 .2160E+02  9 .1000E+01 10 .1000E+01 11 .1000E+01 12 .1000E+01
 13 .1000E+01 14 .1000E+01 15 .1000E+01 16 .1000E+01 17 .1000E+01 18 .1000E+01
 19 .1000E+01 20 .1000E+01 21 .1000E+01 22 .1000E+01 23 .1000E+01 24 .1000E+01
 25 .1000E+01 26 .1000E+01 27 .1000E+01 28 .1000E+01 29 .1000E+01 30 .1000E+01
 31 .1000E+01 32 .1000E+01 33 .1000E+01 34 .1000E+01 35 .1000E+01 36 .1000E+01
 37 .1000E+01 38 .1000E+01 39 .1000E+01 40 .1000E+01 41 .1000E+01 42 .1000E+01
 43 .1000E+01 44 .1000E+01 45 .1000E+01 46 .1000E+01 47 .1000E+01 48 .1000E+01
 49 .1000E+01 50 .1000E+01 51 .1000E+01 52 .1000E+01
INITIAL VALUES OF DEPENDENT VARIABLES
SOIL RESPONSE FACTORS AND TEMPERATURE HISTORY
MMAX= 11  GOOLD =  -.50000E+03  GSOOLD=  -.50000E+03
  BR=   .72749E+00  TD=  18.00  B41=  17.34000
 M      B1          B2         B3      TGO     TGS
  1  39.33360     .00180  46.66130
  2 -51.31760     .22460 -61.45910  19.10   21.70
  3  12.76250     .79040  15.33080  19.60   21.70
  4     .79810    .54850    .97500  20.10   21.80
  5     .18990    .19310    .23880  20.90   21.70
  6     .05260    .05800    .06660  22.10   21.60
  7     .01510    .01690    .01910  23.70   21.30
  8     .00430    .00490    .00550  26.10   21.00
  9     .00130    .00140    .00160  27.80   20.70
 10     .00040    .00040    .00050  28.80   20.40
 11     .00010    .00010    .00010  28.90   20.10

UNIT  5 IS A TYPE 22 MULTISTAGE THERMOSTAT
PARAMETERS
  1 .7000E+01  2 .2000E+02  3 .1300E+02  4 .1550E+02  5 .2400E+02  6 .2650E+02
  7 .2950E+02
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
     1   4  6
INITIAL OUTPUTS
  1 .0000E+00  2 .1000E+01  3 .5000E+00  4 .5000E+00  5 .1000E+01  6 .0000E+00
  7 .1000E+01  8 .0000E+00  9 .1000E+01 10 .0000E+00
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT  6 IS A TYPE 20 ARITHMETIC CALCULATOR
PARAMETERS
  1 .9000E+01  2 .4000E+01  3 .0000E+00  4 .0000E+00  5 .1000E+02  6 .0000E+00
  7 .0000E+00  8 .1000E+02  9 .9000E+01
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
     1   5  6      2   3  2      3   5  8      4   3  1
INITIAL OUTPUTS
  1 .0000E+00  2 .1000E+01
```

```
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT  7 IS A TYPE 20 ARITHMETIC CALCULATOR
PARAMETERS
  1 .5000E+01  2 .2000E+01  3 .0000E+00  4 .0000E+00  5 .9000E+01
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
    1   5  3     2   6  1
INITIAL OUTPUTS
  1 .5000E+00  2 .5000E+00
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT  8 IS A TYPE 20 ARITHMETIC CALCULATOR
PARAMETERS
  1 .6000E+01  2 .1000E+01  3 .0000E+00  4-.1000E+01  5 .4000E+00  6 .1000E+01
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
    1   5 10
INITIAL OUTPUTS
  1 .0000E+00  2 .1000E+01
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT  9 IS A TYPE 16 HEATER
PARAMETERS
  1 .6850E+04  2 .2600E+00  3 .0000E+00
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
    1   4  6     2   9  2     3   4  7     4   5  1
INITIAL OUTPUTS
  1 .2000E+02  2 .0000E+00  3 .0000E+00
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT 10 IS A TYPE  7 TEE
PARAMETERS
. 1 .3000E+01
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
    1   1  9     2   4 51     3   1  6     4   4  6     5   4 51     6   4  7
    7   8  1
INITIAL OUTPUTS
  1 .1500E+02  2 .0000E+00  3 .1000E-01  4 .0000E+00  5 .1800E+01  6 .0000E+00
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT 11 IS A TYPE  6 PUMP OR FAN
PARAMETERS
  1 .3700E+01
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
    1  10  1     2  10  2     3  10  3     4   7  1
INITIAL OUTPUTS
  1 .1500E+02  2 .1800E+01  3 .1000E-01
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT 12 IS A TYPE  6 PUMP OR FAN
PARAMETERS
  1 .3700E+01
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
    1  17  1     2  17  2     3   2  1     4   7  1
INITIAL OUTPUTS
```

```
  1 .1850E+02  2 .1800E+01  3 .0000E+00
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT 13 IS A TYPE  9 LATENT AND SENSIBLE HEAT EXCHANGER
PARAMETERS
  1 .1000E+01  2-.1000E+01  3 .4600E+01  4 .5100E-01  5 .4190E+04  6 .3700E+02
  7 .1460E+01  8 .1000E+00  9 .6500E+05 10 .4000E+00 11 .8300E+00 12 .0000E+00
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
     1  11  1     2  11  2     3  11  3     4  12  1     5  12  2     6   1  8
     7  13  4     8   7  1
INITIAL OUTPUTS
  1 .1550E+02  2 .1800E+01  3 .1000E-01  4 .1550E+02  5 .1800E+01  6 .0000E+00
  7 .0000E+00
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT 14 IS A TYPE  6 PUMP OR FAN
PARAMETERS
  1 .3700E+01
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
     1  17  3     2  17  4     3   2  1     4  19  1
INITIAL OUTPUTS
  1 .1850E+02  2 .0000E+00  3 .0000E+00
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT 15 IS A TYPE  6 PUMP OR FAN
PARAMETERS
  1 .3700E+01
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
     1   1  9     2  15  2     3   1  6     4  19  1
INITIAL OUTPUTS
  1 .1600E+02  2 .0000E+00  3 .0000E+00
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT 16 IS A TYPE  9 LATENT AND SENSIBLE HEAT EXCHANGER
PARAMETERS
  1 .1000E+01  2-.1000E+01  3 .4600E+01  4 .5100E-01  5 .4190E+04  6 .3700E+02
  7 .1460E+01  8 .1000E+00  9 .6500E+05 10 .4000E+00 11 .8300E+00 12 .0000E+00
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
     1  15  1     2  15  2     3  15  3     4  14  1     5  14  2     6   1  8
     7  16  4     8  19  1
INITIAL OUTPUTS
  1 .1600E+02  2 .0000E+00  3 .0000E+00  4 .1600E+02  5 .0000E+00  6 .0000E+00
  7 .0000E+00
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT 17 IS A TYPE 11 FLUID STORAGE TANK
PARAMETERS
  1 .1000E+01  2 .6300E+02  3 .1500E+01  4 .4190E+04  5 .1000E+04  6 .1000E+00
  7 .1850E+02  8 .0000E+00  9 .1000E+01 10 .1000E+01 11 .0000E+00 12 .0000E+00
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
     1  13  4     2  13  5     3  16  4     4  16  5     5   1  9     6   2  1
INITIAL OUTPUTS
  1 .1850E+02  2 .1800E+01  3 .1850E+02  4 .0000E+00  5 .0000E+00  6 .0000E+00
  7 .0000E+00  8 .0000E+00
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INITIAL VALUES OF DEPENDENT VARIABLES
  1 .1850E+02

UNIT 18 IS A TYPE  4 THERMOSTAT
PARAMETERS
  1 .2000E+01  2 .1800E+02  3 .2000E+01
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
     1  17  3     2   1 10
INITIAL OUTPUTS
  1 .1000E+01  2 .0000E+00
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT 19 IS A TYPE 20 ARITHMETIC CALCULATOR
PARAMETERS
  1 .5000E+01  2 .2000E+01  3 .0000E+00  4 .0000E+00  5 .1000E+02
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
     1   3  1     2  18  2
INITIAL OUTPUTS
  1 .0000E+00  2 .1000E+01
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT 20 IS A TYPE 20 ARITHMETIC CALCULATOR
PARAMETERS
  1 .2100E+02  2 .7000E+01  3 .0000E+00  4 .0000E+00  5 .3000E+01  6-.1000E+01
  7 .2450E+07  8 .2000E+01  9 .0000E+00 10 .3000E+01 11 .0000E+00 12 .0000E+00
 13 .1000E+01 14 .0000E+00 15 .0000E+00 16 .4000E+01 17 .1000E+01 18 .3000E+01
 19-.1000E+01 20 .2700E+02 21 .2000E+01
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
     1   4 29     2   4 31     3  16  7     4  11  2     5   8  1     6   4  7
     7   1  6
INITIAL OUTPUTS
  1 .0000E+00  2 .1000E+01
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT 21 IS A TYPE 20 ARITHMETIC CALCULATOR
PARAMETERS
  1 .1600E+02  2 .3000E+01  3 .0000E+00  4-.1000E+01  5 .6850E+04  6 .1000E+01
  7 .0000E+00  8 .0000E+00  9 .3000E+01 10-.1000E+01 11 .1800E+04 12 .1000E+01
 13 .3000E+01 14-.1000E+01 15 .2700E+08 16 .2000E+01
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
     1   5  1     2   7  1     3  19  1
INITIAL OUTPUTS
  1 .0000E+00  2 .1000E+01
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT 22 IS A TYPE 20 ARITHMETIC CALCULATOR
PARAMETERS
  1 .8000E+01  2 .1000E+01  3 .0000E+00  4 .7000E+01  5 .8000E+01  6-.1000E+01
  7 .2700E+08  8 .2000E+01
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
     1  13  6
INITIAL OUTPUTS
  1 .0000E+00  2 .1000E+01
INITIAL VALUES OF DEPENDENT VARIABLES
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UNIT 23 IS A TYPE 20 ARITHMETIC CALCULATOR
PARAMETERS
  1 .7000E+01  2 .1000E+01  3 .0000E+00  4 .8000E+01  5-.1000E+01  6 .2700E+08
  7 .2000E+01
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
    1  13  6
INITIAL OUTPUTS
  1 .0000E+00  2 .1000E+01
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT 24 IS A TYPE 20 ARITHMETIC CALCULATOR
PARAMETERS
  1 .8000E+01  2 .2000E+01  3 .0000E+00  4 .0000E+00  5 .1000E+01  6-.1000E+01
  7 .1000E+07  8 .2000E+01
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
    1   1 12     2   5  9
INITIAL OUTPUTS
  1 .0000E+00  2 .1000E+01
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT 25 IS A TYPE  2 INTEGRATOR
PARAMETERS
  1 .6000E+01  2 .2400E+02  3 .2500E+02
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
    1   1 12     2  20  1     3  21  1     4  22  1     5  23  1     6  24  1
INITIAL OUTPUTS
  1 .0000E+00  2 .0000E+00  3 .0000E+00  4 .0000E+00  5 .0000E+00  6 .0000E+00
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT 26 IS A TYPE  2 INTEGRATOR
PARAMETERS
  1 .6000E+01  2 .8761E+04  3 .2600E+02
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
    1   1 12     2  20  1     3  21  1     4  22  1     5  23  1     6  24  1
INITIAL OUTPUTS
  1 .0000E+00  2 .0000E+00  3 .0000E+00  4 .0000E+00  5 .0000E+00  6 .0000E+00
INITIAL VALUES OF DEPENDENT VARIABLES

UNIT 27 IS A TYPE  3 PRINTER
PARAMETERS
  1 .3400E+02  2 .1000E+01  3 .8000E+02  4 .2700E+02
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
    1   1  1     2   1  2     3   1  3     4   1  4     5   1 12     6   1  9
    7   1  6     8   4  1     9   4  2    10   4  3    11   4  4    12   4  6
   13   4  7    14   4  8    15  17  1    16  13  1    17  13  2    18  13  3
   19  13  4    20  13  5    21  16  4    22  16  5    23   5  1    24   5  3
   25   5  6    26   5  8    27   5 10    28   7  1    29  19  1    30  20  1
   31  21  1    32  22  1    33  23  1    34  24  1
INITIAL OUTPUTS
INITIAL VALUES OF DEPENDENT VARIABLES
 YR MON DAY  HR  SO TAO WAO TCO TCI  TV  TG TAI WAI TGS TTK TAX MAX WAX TLX ML
TLT MLT G13 G15 G24 G26 G29  GX GCT   E   Q  S+  S-  SU
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UNIT 28 IS A TYPE  3 PRINTER
PARAMETERS
  1 .1200E+02  2 .2400E+02  3 .8000E+02  4 .2800E+02
INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)
     1  25  1     2  25  2     3  25  3     4  25  4     5  25  5     6  25  6
     7  26  1     8  26  2     9  26  3    10  26  4    11  26  5    12  26  6
INITIAL OUTPUTS
INITIAL VALUES OF DEPENDENT VARIABLES
  DS  DE  DQ DS+ DS- DSU  AS  AE  AQ AS+ AS- ASU
 FOG ENCOUNTERED IN LXCHNR
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 FOG ENCOUNTERED IN LXCHNR
TIME =     0.00
  YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .000000E+00   SO .00000
 TAO .129000E+02  WAO .818000E-02  TCO .128986E+02  TCI .131032E+02   TV .15094
  TG .169943E+02  TAI .152124E+02  WAI .111212E-01  TGS .211545E+02  TTK .18478
 TAX .156681E+02  MAX .124135E+01  WAX .114875E-01  TLX .181519E+02  MLX .12413
 TLT .184780E+02  MLT .000000E+00  G13 .000000E+00  G15 .335500E+00  G24 .00000
 G26 .000000E+00  G29 .000000E+00   GX .335500E+00  GCT .000000E+00    E .47906
   Q .223666E-04   S+ .000000E+00   S- .187209E-03   SU .000000E+00
TIME =     0.00
  DS .000000E+00   DE .000000E+00   DQ .000000E+00  DS+ .000000E+00  DS- .00000
 DSU .000000E+00   AS .000000E+00   AE .000000E+00   AQ .000000E+00  AS+ .00000
 AS- .000000E+00  ASU .000000E+00
 FOG ENCOUNTERED IN LXCHNR
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 FOG ENCOUNTERED IN LXCHNR
TIME =     1.00
  YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .100000E+01   SO .00000
 TAO .126000E+02  WAO .805000E-02  TCO .131043E+02  TCI .133725E+02   TV .15804
  TG .169328E+02  TAI .160245E+02  WAI .117793E-01  TGS .208882E+02  TTK .18448
 TAX .165756E+02  MAX .201577E+01  WAX .122190E-01  TLX .180562E+02  MLX .20157
 TLT .184488E+02  MLT .000000E+00  G13 .000000E+00  G15 .544801E+00  G24 .00000
 G26 .000000E+00  G29 .000000E+00   GX .544801E+00  GCT .000000E+00    E .69870
   Q .363201E-04   S+ .000000E+00   S- .225440E-03   SU .000000E+00
 FOG ENCOUNTERED IN LXCHNR
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 FOG ENCOUNTERED IN LXCHNR
TIME =     2.00
   YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .200000E+01   SO .00000
  TAO .122000E+02  WAO .789000E-02  TCO .125029E+02  TCI .127462E+02   TV .15065
   TG .166878E+02  TAI .152332E+02  WAI .111647E-01  TGS .206576E+02  TTK .18402
  TAX .157509E+02  MAX .143860E+01  WAX .115700E-01  TLX .180383E+02  MLX .14386
  TLT .184024E+02  MLT .000000E+00  G13 .000000E+00  G15 .389527E+00  G24 .00000
  G26 .000000E+00  G29 .000000E+00   GX .388812E+00  GCT .000000E+00    E .66137
    Q .259208E-04   S+ .000000E+00   S- .209035E-03   SU .000000E+00
 FOG ENCOUNTERED IN LXCHNR
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 FOG ENCOUNTERED IN LXCHNR
TIME =     3.00
   YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .300000E+01   SO .00000
  TAO .116000E+02  WAO .771000E-02  TCO .122476E+02  TCI .125386E+02   TV .15261
   TG .166791E+02  TAI .154795E+02  WAI .113709E-01  TGS .204354E+02  TTK .18367
  TAX .161584E+02  MAX .205656E+01  WAX .118930E-01  TLX .178951E+02  MLX .20565
  TLT .183671E+02  MLT .000000E+00  G13 .000000E+00  G15 .555827E+00  G24 .00000
  G26 .000000E+00  G29 .000000E+00   GX .555827E+00  GCT .000000E+00    E .76565
    Q .370551E-04   S+ .000000E+00   S- .271011E-03   SU .000000E+00
 FOG ENCOUNTERED IN LXCHNR
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 FOG ENCOUNTERED IN LXCHNR
TIME =     4.00
   YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .400000E+01   SO .00000
  TAO .110000E+02  WAO .749000E-02  TCO .118843E+02  TCI .122095E+02   TV .15255
   TG .166721E+02  TAI .154990E+02  WAI .114006E-01  TGS .202181E+02  TTK .18306
  TAX .161488E+02  MAX .200968E+01  WAX .118901E-01  TLX .178602E+02  MLX .20096
  TLT .183061E+02  MLT .000000E+00  G13 .000000E+00  G15 .543156E+00  G24 .00000
  G26 .000000E+00  G29 .000000E+00   GX .543156E+00  GCT .000000E+00    E .82530
    Q .362104E-04   S+ .000000E+00   S- .255997E-03   SU .000000E+00
 FOG ENCOUNTERED IN LXCHNR
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 FOG ENCOUNTERED IN LXCHNR
TIME =     5.00
   YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .500000E+01   SO .00000
  TAO .106000E+02  WAO .731000E-02  TCO .115771E+02  TCI .119146E+02   TV .15104
   TG .166160E+02  TAI .153507E+02  WAI .112935E-01  TGS .200077E+02  TTK .18254
  TAX .160319E+02  MAX .202683E+01  WAX .117997E-01  TLX .177910E+02  MLX .20268
  TLT .182543E+02  MLT .000000E+00  G13 .000000E+00  G15 .547792E+00  G24 .00000
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  G26 .000000E+00  G29 .000000E+00   GX .547792E+00  GCT .000000E+00    E .82745
    Q .365195E-04   S+ .000000E+00   S- .266041E-03   SU .000000E+00
  FOG ENCOUNTERED IN LXCHNR
  FOG ENCOUNTERED IN LXCHNR
  FOG ENCOUNTERED IN LXCHNR
  FOG ENCOUNTERED IN LXCHNR
  FOG ENCOUNTERED IN LXCHNR
 TIME =     6.00
   YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .600000E+01   SO .00000
  TAO .104000E+02  WAO .718000E-02  TCO .115443E+02  TCI .118969E+02   TV .15208
   TG .166191E+02  TAI .154778E+02  WAI .113861E-01  TGS .198064E+02  TTK .18195
  TAX .161690E+02  MAX .219500E+01  WAX .118985E-01  TLX .177265E+02  MLX .21950
  TLT .181958E+02  MLT .000000E+00  G13 .000000E+00  G15 .593243E+00  G24 .00000
  G26 .000000E+00  G29 .000000E+00   GX .593243E+00  GCT .000000E+00    E .83546
    Q .395496E-04   S+ .000000E+00   S- .269509E-03   SU .000000E+00
  FOG ENCOUNTERED IN LXCHNR
  FOG ENCOUNTERED IN LXCHNR
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  FOG ENCOUNTERED IN LXCHNR
  FOG ENCOUNTERED IN LXCHNR
 TIME =     7.00
   YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .700000E+01   SO .50000
  TAO .104000E+02  WAO .707000E-02  TCO .118502E+02  TCI .122298E+02   TV .15739
   TG .167917E+02  TAI .160267E+02  WAI .117968E-01  TGS .196151E+02  TTK .18137
  TAX .166564E+02  MAX .258452E+01  WAX .122682E-01  TLX .177065E+02  MLX .25845
  TLT .181371E+02  MLT .000000E+00  G13 .000000E+00  G15 .698519E+00  G24 .00000
  G26 .000000E+00  G29 .000000E+00   GX .698519E+00  GCT .000000E+00    E .87735
    Q .465679E-04   S+ .000000E+00   S- .247217E-03   SU .500000E-05
  FOG ENCOUNTERED IN LXCHNR
 TIME =     8.00
   YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .800000E+01   SO .21800
  TAO .111000E+02  WAO .703000E-02  TCO .128915E+02  TCI .131448E+02   TV .17729
   TG .179468E+02  TAI .159178E+02  WAI .113882E-01  TGS .194349E+02  TTK .18098
  TAX .162030E+02  MAX .129218E+01  WAX .116945E-01  TLX .178487E+02  MLX .12921
  TLT .180981E+02  MLT .000000E+00  G13 .000000E+00  G15 .349237E+00  G24 .00000
  G26 .000000E+00  G29 .000000E+00   GX .349237E+00  GCT .000000E+00    E .75514
    Q .232824E-04   S+ .000000E+00   S- .143246E-03   SU .218000E-03
 TIME =     9.00
   YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .900000E+01   SO .44900
  TAO .128000E+02  WAO .710000E-02  TCO .159079E+02  TCI .161469E+02   TV .22071
   TG .204393E+02  TAI .188564E+02  WAI .133811E-01  TGS .192722E+02  TTK .18081
  TAX .188564E+02  MAX .000000E+00  WAX .133811E-01  TLX .180810E+02  MLX .00000
  TLT .180810E+02  MLT .000000E+00  G13 .000000E+00  G15 .000000E+00  G24 .00000
  G26 .000000E+00  G29 .000000E+00   GX .000000E+00  GCT .000000E+00    E .10747
    Q .000000E+00   S+ .000000E+00   S- .000000E+00   SU .449000E-03
 TIME =    10.00
   YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .100000E+02   SO .64100
  TAO .152000E+02  WAO .725000E-02  TCO .197378E+02  TCI .200232E+02   TV .26814
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  TG .236936E+02  TAI .228511E+02  WAI .172146E-01  TGS .191467E+02  TTK .18080
 TAX .228511E+02  MAX .000000E+00  WAX .172146E-01  TLX .180803E+02  MLX .00000
 TLT .180803E+02  MLT .000000E+00  G13 .000000E+00  G15 .000000E+00  G24 .00000
 G26 .000000E+00  G29 .000000E+00   GX .000000E+00  GCT .000000E+00    E .17169
   Q .000000E+00   S+ .000000E+00   S- .000000E+00   SU .641000E-03
TIME =    11.00
  YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .110000E+02   SO .77800
 TAO .172000E+02  WAO .729000E-02  TCO .221718E+02  TCI .224343E+02   TV .29530
  TG .264413E+02  TAI .249201E+02  WAI .196021E-01  TGS .190932E+02  TTK .18104
 TAX .242720E+02  MAX .872444E+00  WAX .190522E-01  TLX .185894E+02  MLX .87244
 TLT .181045E+02  MLT .000000E+00  G13 .000000E+00  G15 .000000E+00  G24 .23579
 G26 .000000E+00  G29 .000000E+00   GX .235796E+00  GCT .000000E+00    E .21519
   Q .157197E-04   S+ .278432E-03   S- .000000E+00   SU .778000E-03
TIME =    12.00
  YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .120000E+02   SO .84900
 TAO .188000E+02  WAO .719000E-02  TCO .223094E+02  TCI .223758E+02   TV .29085
  TG .275890E+02  TAI .233234E+02  WAI .179665E-01  TGS .191437E+02  TTK .18152
 TAX .222695E+02  MAX .182850E+01  WAX .171248E-01  TLX .189092E+02  MLX .18285
 TLT .181526E+02  MLT .000000E+00  G13 .000000E+00  G15 .000000E+00  G24 .49418
 G26 .000000E+00  G29 .000000E+00   GX .494188E+00  GCT .000000E+00    E .18891
   Q .329459E-04   S+ .434425E-03   S- .000000E+00   SU .849000E-03
TIME =    13.00
  YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .130000E+02   SO .85100
 TAO .201000E+02  WAO .699000E-02  TCO .236749E+02  TCI .237946E+02   TV .30511
  TG .288912E+02  TAI .252569E+02  WAI .199930E-01  TGS .193058E+02  TTK .18219
 TAX .242510E+02  MAX .131797E+01  WAX .191284E-01  TLX .189785E+02  MLX .13179
 TLT .182191E+02  MLT .000000E+00  G13 .000000E+00  G15 .000000E+00  G24 .35620
 G26 .000000E+00  G29 .000000E+00   GX .356208E+00  GCT .000000E+00    E .24434
   Q .237472E-04   S+ .436044E-03   S- .000000E+00   SU .851000E-03
TIME =    14.00
  YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .140000E+02   SO .78300
 TAO .211000E+02  WAO .677000E-02  TCO .231502E+02  TCI .231434E+02   TV .29047
  TG .287845E+02  TAI .235734E+02  WAI .182410E-01  TGS .195594E+02  TTK .18282
 TAX .223849E+02  MAX .202090E+01  WAX .172853E-01  TLX .191402E+02  MLX .20209
 TLT .182829E+02  MLT .000000E+00  G13 .000000E+00  G15 .000000E+00  G24 .54446
 G26 .000000E+00  G29 .000000E+00   GX .546190E+00  GCT .000000E+00    E .22117
   Q .364127E-04   S+ .492239E-03   S- .000000E+00   SU .783000E-03
TIME =    15.00
  YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .150000E+02   SO .65000
 TAO .221000E+02  WAO .653000E-02  TCO .233527E+02  TCI .234051E+02   TV .28430
  TG .284738E+02  TAI .244388E+02  WAI .187805E-01  TGS .198769E+02  TTK .18386
 TAX .235000E+02  MAX .135066E+01  WAX .181015E-01  TLX .190196E+02  MLX .13506
 TLT .183865E+02  MLT .000000E+00  G13 .000000E+00  G15 .000000E+00  G24 .36662
 G26 .000000E+00  G29 .000000E+00   GX .365042E+00  GCT .000000E+00    E .25217
   Q .243361E-04   S+ .363527E-03   S- .000000E+00   SU .650000E-03
TIME =    16.00
  YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .160000E+02   SO .46100
 TAO .228000E+02  WAO .626000E-02  TCO .231074E+02  TCI .231228E+02   TV .27123
  TG .275442E+02  TAI .239529E+02  WAI .183186E-01  TGS .202236E+02  TTK .18416
 TAX .230833E+02  MAX .135796E+01  WAX .177029E-01  TLX .189946E+02  MLX .13579
 TLT .184161E+02  MLT .000000E+00  G13 .000000E+00  G15 .000000E+00  G24 .36701
 G26 .000000E+00  G29 .000000E+00   GX .367015E+00  GCT .000000E+00    E .26062
   Q .244677E-04   S+ .332114E-03   S- .000000E+00   SU .461000E-03
TIME =    17.00
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   YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .170000E+02   SO .23200
  TAO .228000E+02  WAO .604000E-02  TCO .222966E+02  TCI .223575E+02   TV .25153
   TG .260550E+02  TAI .237325E+02  WAI .177477E-01  TGS .205674E+02  TTK .18438
  TAX .234044E+02  MAX .508529E+00  WAX .175543E-01  TLX .186339E+02  MLX .50852
  TLT .184385E+02  MLT .000000E+00  G13 .000000E+00  G15 .000000E+00  G24 .13744
  G26 .000000E+00  G29 .000000E+00   GX .137440E+00  GCT .000000E+00    E .25350
    Q .916268E-05   S+ .112164E-03   S- .000000E+00   SU .232000E-03
TIME =    18.00
   YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .180000E+02   SO .10000
  TAO .215000E+02  WAO .582000E-02  TCO .194191E+02  TCI .194516E+02   TV .20394
   TG .233927E+02  TAI .206006E+02  WAI .148242E-01  TGS .208801E+02  TTK .18444
  TAX .206006E+02  MAX .000000E+00  WAX .148242E-01  TLX .184448E+02  MLX .00000
  TLT .184448E+02  MLT .000000E+00  G13 .000000E+00  G15 .000000E+00  G24 .00000
  G26 .000000E+00  G29 .000000E+00   GX .000000E+00  GCT .000000E+00    E .17461
    Q .000000E+00   S+ .000000E+00   S- .000000E+00   SU .100000E-04
TIME =    19.00
   YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .190000E+02   SO .00000
  TAO .193000E+02  WAO .562000E-02  TCO .174817E+02  TCI .175548E+02   TV .19020
   TG .218221E+02  TAI .189258E+02  WAI .132382E-01  TGS .211334E+02  TTK .18445
  TAX .189258E+02  MAX .000000E+00  WAX .132382E-01  TLX .184451E+02  MLX .00000
  TLT .184451E+02  MLT .000000E+00  G13 .000000E+00  G15 .000000E+00  G24 .00000
  G26 .000000E+00  G29 .000000E+00   GX .000000E+00  GCT .000000E+00    E .12107
    Q .000000E+00   S+ .000000E+00   S- .000000E+00   SU .000000E+00
TIME =    20.00
   YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .200000E+02   SO .00000
  TAO .178000E+02  WAO .558000E-02  TCO .159672E+02  TCI .160597E+02   TV .17671
   TG .206420E+02  TAI .175375E+02  WAI .122051E-01  TGS .213007E+02  TTK .18445
  TAX .175375E+02  MAX .000000E+00  WAX .122051E-01  TLX .184451E+02  MLX .00000
  TLT .184451E+02  MLT .000000E+00  G13 .000000E+00  G15 .000000E+00  G24 .00000
  G26 .000000E+00  G29 .000000E+00   GX .000000E+00  GCT .000000E+00    E .89182
    Q .000000E+00   S+ .000000E+00   S- .000000E+00   SU .000000E+00
TIME =    21.00
   YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .210000E+02   SO .00000
  TAO .174000E+02  WAO .578000E-02  TCO .155229E+02  TCI .156071E+02   TV .17104
   TG .198549E+02  TAI .169851E+02  WAI .118063E-01  TGS .213775E+02  TTK .18444
  TAX .169851E+02  MAX .000000E+00  WAX .118063E-01  TLX .184449E+02  MLX .00000
  TLT .184449E+02  MLT .000000E+00  G13 .000000E+00  G15 .000000E+00  G24 .00000
  G26 .000000E+00  G29 .000000E+00   GX .000000E+00  GCT .000000E+00    E .80981
    Q .000000E+00   S+ .000000E+00   S- .000000E+00   SU .000000E+00
TIME =    22.00
   YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .220000E+02   SO .00000
  TAO .176000E+02  WAO .615000E-02  TCO .156934E+02  TCI .157587E+02   TV .17025
   TG .193798E+02  TAI .169441E+02  WAI .117855E-01  TGS .213763E+02  TTK .18444
  TAX .169441E+02  MAX .000000E+00  WAX .117855E-01  TLX .184448E+02  MLX .00000
  TLT .184448E+02  MLT .000000E+00  G13 .000000E+00  G15 .000000E+00  G24 .00000
  G26 .000000E+00  G29 .000000E+00   GX .000000E+00  GCT .000000E+00    E .82012
    Q .000000E+00   S+ .000000E+00   S- .000000E+00   SU .000000E+00
TIME =    23.00
   YR .780000E+02  MON .300000E+01  DAY .700000E+01   HR .230000E+02   SO .00000
  TAO .172000E+02  WAO .651000E-02  TCO .154484E+02  TCI .155095E+02   TV .16716
   TG .189647E+02  TAI .166380E+02  WAI .115743E-01  TGS .213153E+02  TTK .18444
  TAX .166380E+02  MAX .000000E+00  WAX .115743E-01  TLX .184446E+02  MLX .00000
  TLT .184446E+02  MLT .000000E+00  G13 .000000E+00  G15 .000000E+00  G24 .00000
  G26 .000000E+00  G29 .000000E+00   GX .000000E+00  GCT .000000E+00    E .78141
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```
   Q .000000E+00   S+ .000000E+00   S- .000000E+00   SU .000000E+00
TIME =    24.00
  YR .780000E+02  MON .300000E+01  DAY .800000E+01   HR .000000E+00   SO .00000
 TAO .158000E+02  WAO .681000E-02  TCO .144106E+02  TCI .144880E+02   TV .15873
  TG .184239E+02  TAI .157496E+02  WAI .109621E-01  TGS .212129E+02  TTK .18444
 TAX .157496E+02  MAX .000000E+00  WAX .109621E-01  TLX .184443E+02  MLX .00000
 TLT .184443E+02  MLT .000000E+00  G13 .000000E+00  G15 .000000E+00  G24 .00000
 G26 .000000E+00  G29 .000000E+00   GX .000000E+00  GCT .000000E+00    E .65389
   Q .000000E+00   S+ .000000E+00   S- .000000E+00   SU .000000E+00
TIME =    24.00
  DS .213372E+08   DE .116006E+01   DQ .165384E+01  DS+ .881620E+01  DS- .71319
 DSU .213372E+02   AS .213372E+08   AE .116006E+01   AQ .165384E+01  AS+ .88162
 AS- .713196E+01  ASU .213372E+02
```

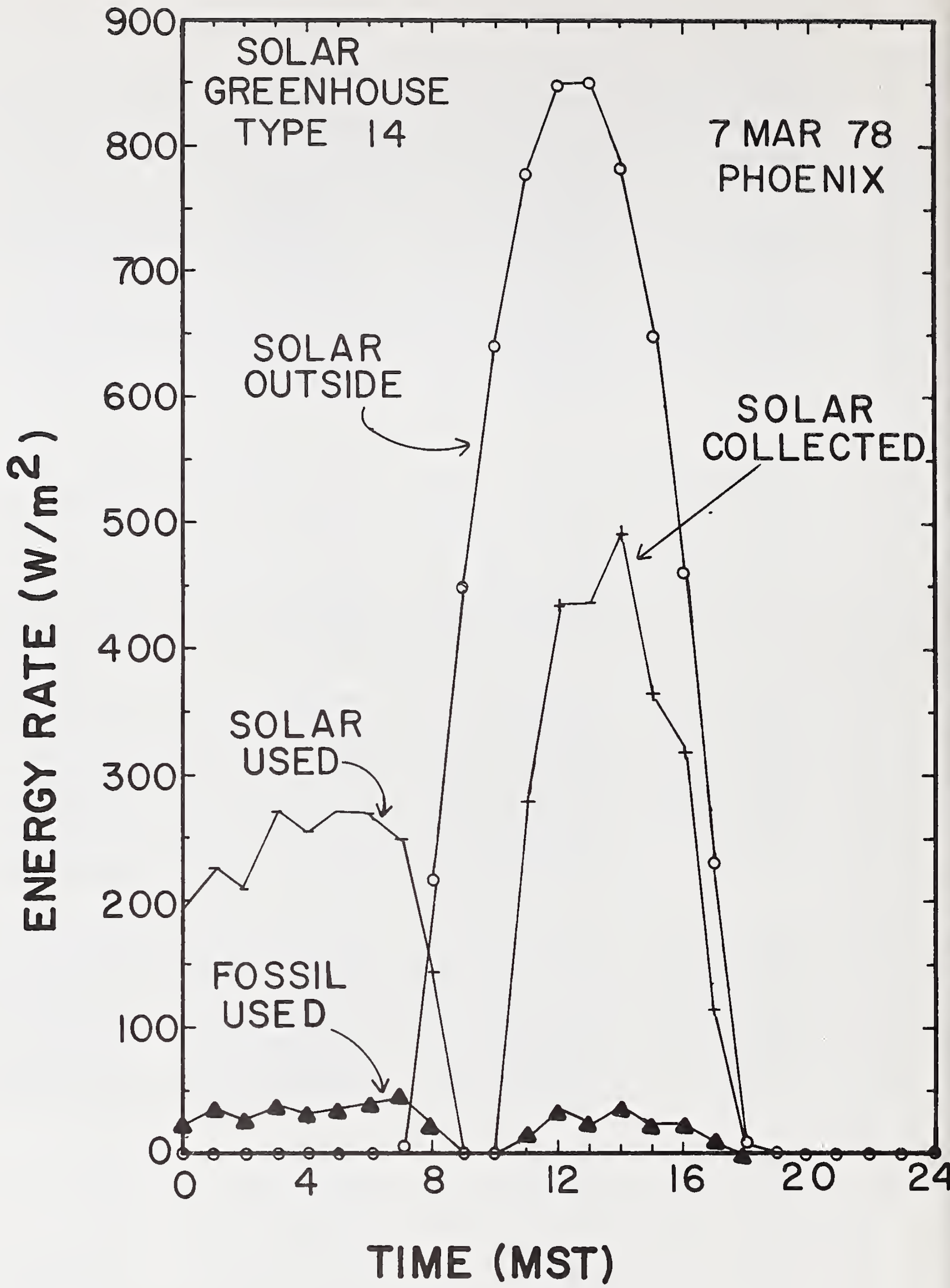

Figure 38.
Solar energy outside, solar energy collected, solar energy used, and fossil energy used versus time of day for solar greenhouse system example.

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Appendix A: Nomenclature for main program and subroutine INIT

ARITH	Type 20 Arithmetic Calculator subroutine
BR	common ratio for conduction on transfer functions in Type 14 Complicated Greenhouse
BRF(4,)	array of conduction transfer functions for Type 14 Completed Greenhouse
CD(, 7)	storage array used by Type 4 Thermostat. The first dimension must be as large as the maximum number of Type 4 Thermostats to be used in the same simulation, and the second dimension should be 7.
CGH	Type 14 Complicated Greenhouse subroutine
CLECR	Type 10 Solar Collector subroutine
COOLR	Type 18 Evaporative Cooler subroutine
CXR	Type 23 Curtain Heat Exchanger subroutine
DELT	time increment between simulation times (seconds)
DTDT( )	array of derivatives. Data stored in same fashion as in OUTPUT.
DTDTI( )	array of derivatives from an individual subroutine model. Must be dimensioned larger than the number of derivatives in the subroutine having the most derivatives.
DTDTO( )	storage array for old values of DTDT( )
ERR	statement number to be executed upon an error return after attempting to OPEN a file
ETOL	relative error tolerance for convergence
FAN	Type 6 Fan or Pump subroutine
FTIME	Hewlett-Packard RTE-IVB operating system subroutine for obtaining the actual date and time user is making simulation run
FTRACE	time at which printing of all inputs, outputs, and derivatives of all units for every iteration will begin. This allows tracing of input-output connections and other error detection.
GH	Type 5 Greenhouse subroutine

GHOLD(8)	storage array used by Type 14 Greenhouse
GHTIME	time storage for Type 14 Complicated Greenhouse
GS(3)	soil heat fluxes for Type 14 Complicated Greenhouse
GSOLD(3)	old values of GS( )
GSUM(4)	array of sums of products between conduction transfer functions and past temperatures for Type 14 Complicated Greenhouse
HEATR	Type 16 Heater subroutine
HDELT	half of DELT
IBUF( )	integer array buffer for storing the actual data and time user is making simulation run
ICFLAG	flag for checking convergence
IDTDT	index for derivatives
IDTDTF	first subscript for derivatives
IDTDTL	last subscript for derivatives
IERR	error code
IGUESS	initial guess flag used by Type 14 Greenhouse
IIN	index for inputs
IINF	first subscript for input
IINL	last subscript for input
INDATA	variable code name of file or device where input data for simulation is to be read
INGTR	Type 2 Integrator subroutine
INIT	name of subroutine for initializing system
INSTN	statement number to execute after successful load of a program overlay segment
IOS	error code
IOUT	index for outputs
IOUTF	first subscript for output

IOUTL	last subscript for output
IPAR	index for parameters. Also integer array in small program segment overlay main programs.
IPARF	first subscript for parameter
IPARL	last subscript for parameter
ISU( )	array of unit numbers for Type 2 Integrators. Must be dimensioned larger than total number of Integrators in system.
ITERD	iteration counter and index for the derivatives loop
ITERO	iteration counter and index for the outputs loop
ITIME	DO loop index for timer
ITITLE( )	storage array for title of simulation run (maximum of 80 characters)
ITMAX	maximum number of iterations
IUNIT	DO loop index for identifying particular units
IUSEG( )	Array containing the number of the program overlay segment containing the subroutine given by the subscript, i.e., if IUSEG(5) = 2, then the subroutine for the Type 5 Greenhouse is in Segment 2.
IV	flag to indicate which program overlay segment is in memory
KARTYP(,)	two dimensional array containing basic programming information about each type of device. The first subscript is the type number. The second has the following code: KARTYP (ITYPE, 1) - no. parameters KARTYP (ITYPE, 2) - no. inputs KARTYP (ITYPE, 3) - no outputs KARTYP (ITYPE, 4) - no. derivatives KARTYP (,4) - must be dimensioned to the number of types for the first subscript and 4 for the second
KLMIT	variable code name of file or device where weather data is to be read by the Type 1 Reader
KNVRG	flag for checking convergence
KNVRG2	flag used to inhibit calling the Type 2 Integrator and the Type 3 Printer before convergence of outputs and derivatives is achieved

KONECT(,2)	two-dimensional array containing the unit and output number that the inputs of a device are connected to. The first subscript denotes in consecutive order the inputs for the first unit, then the second, etc., as with the output array. The second subscript is either a 1 denoting the connecting device number or 2 denoting the output number of that particular device.
KOUT	variable code name of file or device where output data is to be written
KSUBS(NUNITS,4,2)	three-dimensional array for storing the first and last subscripts which indicate where the data are stored in the OUTPUT, KONECT, PAR, and DTDT arrays. The first subscript is the unit number. The code for the second is: 1, parameters; 2, inputs; 3, outputs; 4, derivatives. The code for the third is: 1 first subscript, 2 last subscript.
KTP	index for type of device. It is the type of the IUNIT th unit.
KTROL	number of particular Type 4 Thermostat in system
KTYPE	type of the IUNIT th unit
KTYPU( )	array of type numbers; i.e., KTYPU(3) is the type of unit 3. KTYPU must be dimensioned to the maximum number of units.
LABEL(2, ,)	array of labels for Type 3 Printers. The second subscript must be dimensioned to the maximum number of inputs (XIN( )), and the third subscript to the maximum number of Type 3 Printers in a system.
LABU( )	array of unit numbers for Type 3 Printers. Must be dimensioned to maximum number of Printers in system.
LUTERM	device code number of user's terminal
LXR	Type 9 Latent and Sensible Heat Exchanger subroutine
MEBDI	name of data input file which contains all the information for defining a simulation system.
MEBVØ	name of program overlay segment for Subroutine INIT
MEBV1	name of program overlay segment
MEBV2	name of program overlay segment
MEBV3	name of program overlay segment

MITER	maximum number of iterations before Type 22 Multistage Thermostat fixes outputs
MMAX	maximum number of conduction transfer functions for Type 14 Complicated Greenhouse
MSTAT	Type 22 Multistage Thermostat subroutine
NAME( )	integer array name of weather data file
NAMEO( )	integer array name or device code where output of simulation run is to be printed
NDTDTS	total number of derivatives from all devices
NOUTS	total number of outputs from all devices
NPRT	number of particular Type 3 Printer in system
NSRAD	Type 17 Night Sky Radiator subroutine
NTGR	number of particular Type 2 Integrator in system
NTIMES	number of times simulation is to be done
NUNITS	number of units or devices connected together in the system
OLDIN( )	array of outputs from previous iteration. Storage is the same as the OUTPUT( ) array. OLDIN is used to test whether the inputs to an individual subroutine have changed since the previous iteration.
OPEN	Hewlett-Packard RTE-IVB operating system subroutine for opening disk files or devices
OSTAT	Type 21 On-Off Thermostat subroutine
OUTI( )	array of outputs from an individual subroutine model must be dimensioned larger than the number of outputs required by the individual subroutine having the most outputs.
OUTOLD( )	storage array for old values of output
OUTPUT( )	array of outputs from all the units, stored in consecutive order with the outputs from the first unit first, then those from the second unit, etc. If a unit has no outputs, it is skipped, and the outputs from the units with numbers on each side of the unit with no outputs are next to each other.

PAR( )	array of parameters for all the units. Data stored in same fashion as in OUTPUT
PARI( )	array of parameters from an individual subroutine model. Must be dimensioned larger than the number of parameters required by the subroutine having the most parameters.
PRNTR	Type 3 Printer subroutine
PSTOR	Type 24 Passive Storage subroutine
READR	Type 1 Reader subroutine
REL	relative error
RMPAR	Hewlett-Packard RTE-IVB operating system subroutine for getting program overlay segment parameters.
ROCK	Type 19 Rock Bed subroutine
RSVOR	Type 13 Reservoir subroutine
SDA	first day in weather data file for start of simulation
SEGLD	Hewlett-Packard RTE-IVB operating system subroutine for loading program overlay segments
SGH	Type 15 Simple Greenhouse subroutine
SHR	first hour in weather data file for start of simulation
SMN	first month in weather data file for start of simulation
STORX(,)	accumulator array used by Type 2 Integrator. The first subscript must be dimensioned larger than the maximum number of inputs to be integrated, and the second larger than the total number of Type 2 Integrators in the system.
STRACE	time at which printing all inputs, outputs, and derivatives will stop
SXR	Type 8 Sensible Heat Exchanger subroutine
SYR	First year in weather data file for start of simulation (2 digit)
T( )	array of time-dependent variables which have derivatives to be evaluated. Data stored in same fashion as in OUTPUT.
TAIOLD	old value of inside greenhouse air temperature used by Type 5 Greenhouse

TANK	Type 11 Tank subroutine
TC ( )	temporary storage array for corrected T's
TCOLD	old value of cover temperature used by Type 5 Greenhouse
TCOV	cover temperature for Type 17 Night Sky Radiator
TD	soil temperature at great depth in Type 14 Complicated Greenhouse
TEE	Type 7 Tee subroutine subroutine
TGØOLD	array of past soil surface temperatures in Type 14 Complicated Greenhouse
TGSOLD	array of past soil storage temperatures in Type 14 Complicated Greenhouse
TI ( )	array of dependent variables requiring integration to an individual subroutine model. Must be dimensioned larger than the number of derivatives in the subroutine having the most derivatives.
TIME	elapsed time since start of simulation (hours)
TIMFN	Type 12 Time Function subroutine
TIMMST	time storage for Type 22 Multistage Thermostat
TMS(,5)	storage array for Type 22 Multistage Thermostats. The first subscript should be dimensioned to the maximum number of set points, and the second dimension should be 5.
TOLD( )	storage array for old values of T( )
TSTAT	Type 4 Thermostat subroutine
TSUR	surface temperature for Type 17 Night Sky Radiator
WAIOLD	old value of inside air humidity ratio used by Type 5 Greenhouse
XIN( )	array of inputs to an individual subroutine model. Must be dimensioned larger than the number of inputs required by the individual subroutine having the most inputs.
XOLD(,)	storage array used by Type 2 Integrator. Dimensioned like STORX(,)

Appendix B: Subroutine or file name codes

Type	Device or Program	Subroutine or File Name
	Main Executive Program	MEBM
	Initialization	INIT
1	Reader	READR
2	Integrator	INGTR
3	Printer	PRNTR
4	Thermostat	TSTAT
5	Greenhouse	GH
6	Pump or Fan	FAN
7	Tee	TEE
8	Sensible Heat Exchanger	SXR
9	Latent and Sensible Heat Exchanger	LXR
10	Solar Collector	CLECR
11	Water Tank	TANK
12	Time Dependent Forcing Function	TIMFN
13	Reservoir	RSVOR
14	Complicated Greenhouse	CGH
15	Simple Greenhouse	SGH
16	Heater	HEATR
17	Night Sky Radiator	NSRAD
18	Evaporative Air Cooler	COOLR
19	Rock Bed Thermal Storage	ROCK
20	Arithmetic Calculator	ARITH
21	On-Off Thermostat	OSTAT
22	Multistage Thermostat	MSTAT
23	Curtain Heat Exchanger	CXR
24	Passive Storage	PSTOR
	Data input file of simulation information	MEBDI

```
$FILES(2,3)
      PROGRAM MEBM(3)
C
C                MODULAR ENERGY BALANCE MODEL
C
C       MAIN PROGRAM.  PROGRAMMED BY B. A. KIMBALL, U. S. WATER
C       CONSERVATION LABORATORY, PHOENIX, ARIZONA. 1979.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      COMMON ETOL,ITMAX,NTIMES,FTRACE,STRACE,DELT,HDELT
      COMMON NOUTS,NDTDTS,NUNITS
      COMMON KTYPU(40),KSUBS(40,4,2),KONECT(200,2),PAR(350)
      COMMON OUTPUT(200),OUTOLD(200),OLDIN(200)
      COMMON T(20),TOLD(20),TC(20),DTDT(20),DTDTO(20)
      COMMON/STRT/SYR,SMN,SDA,SHR
      COMMON/LAB1/KARTYP(40,4),IUSEG(40)
      COMMON/FILES/INDATA,KLMIT,KOUT,LUTERM
      COMMON/STRGE/STORX(4,20),XOLD(4,20),ISU(4)
      COMMON/GHMN/TAIOLD,TCOLD,WAIOLD
      COMMON/CGHMN/GHOLD(8),MMAX,BR,GS(3),GSOLD(3),GSUM(4),TD,
     1    BRF(4,24),TGOOLD(26),TGSOLD(26),GHTIME
      COMMON/NSR/TCOV,TSUR
      COMMON/LB/LABEL(2,40,5),LABU(5)
      COMMON/CNTRL/CD(10,8)
      COMMON/MSTOR/TMS(10,5),TIMMST,MITER
C
COVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOV
C     INITIALIZE THE NAMES OF THE PROGRAM SEGMENTS
      DIMENSION MEBV0(3),MEBV1(3),MEBV2(3),MEBV3(3)
      DATA MEBV0/2HME,2HBV,2H0 /
      DATA MEBV1/2HME,2HBV,2H1 /
      DATA MEBV2/2HME,2HBV,2H2 /
      DATA MEBV3/2HME,2HBV,2H3 /
C
C     LOAD SEGMENT WITH SR INIT
      ASSIGN 100 TO INSTN
      CALL SEGLD(MEBV0,IERR,INSTN)
      WRITE(KOUT,430) IERR
  430 FORMAT(" ERROR",I3," IN ATTEMPT TO LOAD INITIALIZATION SEGMENT")
      STOP
C
C     INITIALIZE CONDITIONAL SEGMENT LOAD FLAG
  100 IV=0
COVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOV
C
C      INITIALIZE RUN PARAMETERS
      CALL INIT
C
C                START LOOP FOR TIMES
      DO 999 ITIME=1,NTIMES
```

```
      TIME=FLOAT(ITIME-1)*DELT/3600.
      IF(TIME.GE.FTRACE.AND.TIME.LE.STRACE)WRITE(KOUT,231)ITIME,TIME
  231 FORMAT("   "//" TIME ",I4," = ",F10.2)
C
C      COMPUTE PREDICTED VALUE OF T
      IF(NDTDTS.EQ.0) GOTO 202
      DO 201 IDTDT=1,NDTDTS
      TOLD(IDTDT)=T(IDTDT)
      DTDTO(IDTDT)=DTDT(IDTDT)
      T(IDTDT)=TOLD(IDTDT) + DELT*DTDTO(IDTDT)
     IF(TIME.GE.FTRACE.AND.TIME.LE.STRACE)WRITE(KOUT,232)IDTDT,T(IDTDT)
  232 FORMAT(" T PRED (",I2,")=",E14.6)
  201 CONTINUE
C
  202 IF(TIME.GE.FTRACE .AND. TIME.LE.STRACE) WRITE(LUTERM,233)
  233 FORMAT(" IUNIT ITERO ITERD")
C
C      START OUTER LOOP FOR OBTAINING CONVERGENCE OF DERIVATIVEQ
      KNVRG2=1
      ITERD=0
  200 ITERD=ITERD + 1
C
C
C      START INNER LOOP FOR CONVERGENCE OF OUTPUTS
      ITERO=0.
  300 ITERO=ITERO+1
C
C
C      START LOOP FOR CALLING EACH UNIT IN SEQUENCE
      DO 319 IUNIT=1,NUNITS
C
C     GET THE TYPE OF UNIT
      KTYPE=KTYPU(IUNIT)
C
C     ONLY CALL THE TYPE 1 READER ONCE FOR EACH TIME
      IF(KTYPE.EQ.1 .AND. ITERD.GT.1) GOTO 319
      IF(KTYPE.EQ.1 .AND. ITERD.EQ.1 .AND. ITERO.GT.1) GOTO 319
C
C     DON'T CALL TYPE 2 INTEGRATORS OR TYPE 3 PRINTERS UNLESS
C     HAVE CONVERGENCE, AND IF HAVE CONVERGENCE, THEN DON'T
C     CALL ANY OTHER DEVICE TYPES.
      IF(KNVRG2.LT.3 .AND. KTYPE.EQ.2) GOTO 319
      IF(KNVRG2.LT.3 .AND. KTYPE.EQ.3) GOTO 319
      IF(KNVRG2.GE.3 .AND. KTYPE.NE.2 .AND. KTYPE.NE.3) GOTO 319
C
      IF(TIME.GE.FTRACE.AND.TIME.LE.STRACE)
     1     WRITE(LUTERM,340)IUNIT,ITERO,ITERD
  340 FORMAT(1X,3I3)
      IF(TIME.GE.FTRACE .AND. TIME.LE.STRACE)
     1  WRITE(KOUT,341) IUNIT,ITERO,ITERD
```

```
 341   FORMAT(/" IUNIT=",I3,"   ITERO=",I3,"   ITERD=",I3)
C
C
C       GET THE INPUTS FOR THE IUNIT TH UNIT.  THEY ARE CONNECTED
C       TO THE OUPUTS OF OTHER UNITS AS DEFINED BY THE KONECT ARRAY.
       IINF=KSUBS(IUNIT,2,1)
C      IF DEVICE HAS NO INPUTS, ONLY CALL ON FIRST OUTPUT ITERATION
       IF(IINF.EQ.-1 .AND. ITERO.GT.1) GOTO 319
       IF(IINF.EQ.-1) GOTO 302
       IINL=KSUBS(IUNIT,2,2)
       ICFLAG=+1
       DO 301 IIN=IINF,IINL
C       IDV IS DEVICE WHOSE OUTPUT IS CONNECTED TO IUNIT
       IDV=KONECT(IIN,1)
C       IDVO IS OUTPUT NO. OF OUTPUT OF DEVICE THAT IS
C       CONNECTED TO IUNIT
       IDVO=KONECT(IIN,2)
       KS=KSUBS(IDV,3,1) + IDVO -1
       XIN(IIN-IINF+1)=OUTPUT(KS)
C
C       CHECK TO SEE IF INPUTS TO IUNIT TH UNIT CHANGED SINCE LAST
C      ITERATION.
       IF(ITERO.EQ.1) GOTO 301
       IF(ABS(OUTPUT(KS)).LE.1.E-10) GOTO 332
       REL = ABS((OUTPUT(KS)-OLDIN(KS))/OUTPUT(KS))
       IF(REL .GT. ETOL) ICFLAG = -1
       GOTO 301
  332 IF(ABS(OUTPUT(KS)-OLDIN(KS)).GT. ETOL) ICFLAG= -1
  301 CONTINUE
C
C       IF NO CHANGES IN INPUTS DON'T CALL THIS UNIT
C       EXCEPTIONS: ALL UNITS CALLED FIRST AND SECOND ITERATIONS
       IF(ICFLAG.EQ.1 .AND. ITERO.GT.2) GOTO 319
       II=IINL-IINF+1
       IF(TIME.GE.FTRACE .AND. TIME.LE.STRACE)
     1     WRITE(KOUT,323)(IIN,XIN(IIN),IIN=1,II)
  323 FORMAT(" INPUTS"/(1H ,5(I4,E12.6)))
C
C       GET THE VALUES OF THE VARIABLES WHICH HAVE DERIVATIVES FOR THE
C       IUNIT TH UNIT.
  302 IDTDTF=KSUBS(IUNIT,4,1)
       IF(IDTDTF.EQ.-1) GOTO 305
       IDTDTL=KSUBS(IUNIT,4,2)
       DO 306 IDTDT=IDTDTF,IDTDTL
       TI(IDTDT-IDTDTF+1)=T(IDTDT)
  306 CONTINUE
C
C       GET THE PARAMETERS FOR THE IUNIT TH UNIT
  305 IPARF=KSUBS(IUNIT,1,1)
       IF(IPARF.EQ.-1) GOTO 304
```

```
       IPARL=KSUBS(IUNIT,1,2)
       DO 303 IPAR=IPARF,IPARL
       PARI(IPAR-IPARF+1)=PAR(IPAR)
  303 CONTINUE
C
COVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOV
C     CHECK WHETHER THE PROGAM SEGMENT IN MEMORY CONTAINS THE SR
C     FOR THE PARTICULAR UNIT
  304 IF(IUSEG(KTYPE).EQ.IV) GOTO 339
C     LOAD APPROPRIATE PROGRAM SEGMENT
      ASSIGN 339 TO INSTN
      GOTO (401,402,403) IUSEG(KTYPE)
 401  IV=1
      CALL SEGLD(MEBV1,IERR,INSTN)
      GOTO 420
 402  IV=2
      CALL SEGLD(MEBV2,IERR,INSTN)
      GOTO 420
 403  IV=3
      CALL SEGLD(MEBV3,IERR,INSTN)
      GOTO 420
 420  WRITE(KOUT,421) IERR,IUSEG(KTYPE),KTYPE
 421  FORMAT(" ERROR",I4," IN ATTEMPT TO LOAD SEGMENT",I3,
     1   " FOR A TYPE",I3," DEVICE")
      STOP
COVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOV
C
C     CALL THE SUBROUTINE FOR THE PARTICULAR TYPE OF UNIT
 339   GOTO (1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,
     1      23,24) KTYPE
C
    1  CALL READR
       GOTO 310
    2  CALL INGTR
       GOTO 310
    3  CALL PRNTR
       GOTO 310
    4  CALL TSTAT
       GOTO 310
    5  CALL GH
       GOTO 310
    6  CALL FAN
       GOTO 310
    7  CALL TEE
       GOTO 310
    8  CALL SXR
       GOTO 310
    9  CALL LXR
       GOTO 310
   10  CALL CLECR
```

```
      GOTO 310
   11 CALL TANK
      GOTO 310
   12 CALL TIMFN
      GOTO 310
   13 CALL RSVOR
      GOTO 310
   14 CALL CGH
      GOTO 310
   15 CALL SGH
      GOTO 310
   16 CALL HEATR
      GOTO 310
   17 CALL NSRAD
      GOTO 310
   18 CALL COOLR
      GOTO 310
   19 CALL ROCK
      GOTO 310
   20 CALL ARITH
      GOTO 310
   21 CALL OSTAT
      GOTO 310
   22 CALL MSTAT
      GOTO 310
   23 CALL CXR
      GOTO 310
   24 CALL PSTOR
      GOTO 310
C
C        STORE THE INDIVIDUAL OUTPUTS
  310 IOUTF=KSUBS(IUNIT,3,1)
      IF(IOUTF.EQ.-1) GOTO 312
      IOUTL=KSUBS(IUNIT,3,2)
      II=IOUTL-IOUTF+1
      IF(TIME.GE.FTRACE .AND. TIME.LE.STRACE)
     1    WRITE(KOUT,322)(IOUT,OUTI(IOUT),IOUT=1,II)
  322 FORMAT(" OUTPUTS"/(1H ,5(I4,E12.6)))
      DO 311 IOUT=IOUTF,IOUTL
      OUTPUT(IOUT)=OUTI(IOUT-IOUTF+1)
  311 CONTINUE
C
C        STORE THE INDIVIDUAL DERIVATIVES
  312 IDTDTF=KSUBS(IUNIT,4,1)
      IF(IDTDTF.EQ.-1) GOTO 319
      IDTDTL=KSUBS(IUNIT,4,2)
      II=IDTDTL-IDTDTF+1
      IF(TIME.GE.FTRACE .AND. TIME.LE.STRACE)
     1  WRITE(KOUT,222)(IDTDT,TI(IDTDT),DTDTI(IDTDT),IDTDT=1,II)
  222 FORMAT(" T DTDT"/2(2X,I4,2E13.6))
```

```
      DO 313 IDTDT=IDTDTF,IDTDTL
      DTDT(IDTDT)=DTDTI(IDTDT-IDTDTF+1)
  313 CONTINUE
C
  319  CONTINUE
C
C
       IF(KNVRG2.EQ.3) GOTO 999
C
C        TEST FOR CONVERGENCE OF THE OUTPUTS
       KNVRG=+1
       DO 330 IOUT=1,NOUTS
       IF(ABS(OUTPUT(IOUT)).LE. 1.E-10) GOTO 320
       REL=ABS((OUTPUT(IOUT) - OUTOLD(IOUT))/OUTPUT(IOUT))
       IF(REL.GT.ETOL) KNVRG=-1
       GOTO 321
  320 IF(ABS(OUTPUT(IOUT)-OUTOLD(IOUT)).GT.ETOL) KNVRG=-1
C        TEST MADE - UPDATE OLD VALUES OF OUTPUT
  321 OLDIN(IOUT)=OUTOLD(IOUT)
       OUTOLD(IOUT)=OUTPUT(IOUT)
  330 CONTINUE
C
C        IF KNVRG=+1, CONVERGENCE OF OUPUTS IS ATTAINED.  GO BACK TO
C       OUTER LOOP
       IF(KNVRG.EQ.+1) GOTO 210
C        IF KNVRG=-1, CONVERGENCE NOT ATTAINED.  CHECK NO. OF ITERATIONS
C        AND GO BACK.
       IF(ITERO.LT.ITMAX) GOTO 300
       WRITE(KOUT,331) TIME,ITERD,ITERO
  331 FORMAT(" ***WARNING CONVERGENCE NOT ATTAINED AT TIME = ",F10.3/
     1   12X,"DERIVATIVE ITERATIONS = ",I5/
     2   12X,"OUTPUT     ITERATIONS = ",I5)
       GOTO 210
C
C
C        COMPUTE CORRECTED VALUES OF DEPENDENT VARIABLES WHICH HAVE
C        DERIVATIVES
  210 IF(NDTDTS.EQ.0) GOTO 998
       DO 211 IDTDT=1,NDTDTS
       IF(ITIME.GT.1)
     1 TC(IDTDT)=TOLD(IDTDT) + HDELT*(DTDT(IDTDT) + DTDTO(IDTDT))
       IF(ITIME.EQ.1) TC(IDTDT) = TOLD(IDTDT) + DELT*DTDT(IDTDT)
  211 CONTINUE
C
C        TEST FOR CONVERGENCE OF OUTER DERIVATIVE LOOP
       KNVRG=+1
       DO 230 IDTDT=1,NDTDTS
       IF(ABS(TC(IDTDT)).LE. 1.E-10) GOTO 220
       REL=ABS((TC(IDTDT)-T(IDTDT))/TC(IDTDT))
       IF(REL.GT.ETOL) KNVRG=-1
```

```
      GOTO 221
  220 IF(ABS(TC(IDTDT)-T(IDTDT)).GT.ETOL) KNVRG=-1
C       TEST COMPLTETED, UPDATE CORRECTED  VALUES
  221 T(IDTDT)=TC(IDTDT)
  230 CONTINUE
C
C       IF KNVRG=-1, CONVERGENCE OF DERIVATIVES NOT ATTAINED.  CHECK
C       NO. OF ITERATIONS AND GO BACK.
  998 IF(KNVRG.EQ.+1) KNVRG2=KNVRG2+1
      IF(ITERD.LT.ITMAX) GOTO 200
      WRITE(KOUT,331) TIME,ITERD,ITERO
C
C
  999 CONTINUE
C
      STOP
      END
```

```
C
      BLOCK DATA MEBBD
      COMMON/STRT/SYR,SMN,SDA,SHR
      COMMON/LAB1/KARTYP(40,4),IUSEG(40)
      COMMON/FILES/INDATA,KLMIT,KOUT,LUTERM
      COMMON/STRGE/STORX(4,20),XOLD(4,20),ISU(4)
      COMMON/GHMN/TAIOLD,TCOLD,WAIOLD
      COMMON/CGHMN/GHOLD(8),MMAX,BR,GS(3),GSOLD(3),GSUM(4),TD,
     1  BRF(4,24),TGOOLD(26),TGSOLD(26),GHTIME
      COMMON/NSR/TCOV,TSUR
      COMMON/LB/LABEL(2,40,5),LABU(5)
      COMMON/CNTRL/CD(10,8)
      COMMON/MSTOR/TMS(10,5),TIMMST,MITER
C
C     INITIALIZE I/O FILE NAMES AND NOS
      DATA INDATA/1/,KLMIT/2/,KOUT/6/,LUTERM/7/
C
C      INITIALIZE ARRAY OF CHARACTERISTICS OF THE VARIOUS TYPES OF
C      DEVICES IN THE ORDER BY LINE - NO. PARAMETERS, NO. INPUTS,
C      NO. OUTPUTS, NO. DERIVATIVES
C TYPE NO  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20
C     OR 21 22 23 24 25 26 27 28 29 40 31 32 33 34 35 36 37 38 39 80
      DATA KARTYP/
     P    0, 3, 4, 3,99, 1, 1, 4,12,12,12,99,81,76,18, 3,17, 2, 8,99,
     P    2,42, 2, 4, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
     I    0,40,40, 2,40, 4, 7, 5, 8, 8, 6, 0, 0,40,40, 4, 9, 5,10,40,
     I    2, 1, 5, 3, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
     O   23,40, 0, 2,80, 3, 6, 6, 7, 5, 8, 2,80,80, 6, 3, 8, 4,21, 2,
     O    2,40, 6, 5, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
     D    0, 0, 0, 0,10, 0, 0, 0, 0, 0,10, 0, 0, 0, 0, 0, 0, 0,10, 0,
     D    0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0/
C
COVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOV
C     INITIALIZE PROGRAM SEGMENT NO. EACH UNIT IS IN
      DATA IUSEG/
     S    1, 1, 1, 1, 2, 1, 1, 2, 1, 2, 1, 1, 1, 3, 2, 1, 2, 1, 2, 1,
     S    1, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0/
COVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOV
C
      END
```

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PAGE    1   FTN.    OPTS:   LYI          10:49 AM  TUE., 30  NOV., 1982

COVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOV
      PROGRAM MEBVO(5)
      DIMENSION IPAR(5)
      CALL RMPAR(IPAR)
      INSTN=IPAR(1)
      GOTO INSTN
      END
```

```
COVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOV
C
      SUBROUTINE INIT
C
C            THIS SUBROUTINE READS THE INFORMATION ABOUT THIS
C      PARTICULAR RUN IN FROM A DISK FILE, AND INITIALIZES
C      ALL THE VARIABLES HAVING TO DO WITH THE TIMES OF THE
C      SIMULATION, THE NUMBER OF DEVICES OR UNITS AND THE TYPE OF
C      EACH, ETC.
C
C            PROGRAMMED BY B. A. KIMBALL, U. S. WATER CONSERVATION
C      LABORATORY, PHOENIX, ARIZONA.  1979.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      COMMON ETOL,ITMAX,NTIMES,FTRACE,STRACE,DELT,HDELT
      COMMON NOUTS,NDTDTS,NUNITS
      COMMON KTYPU(40),KSUBS(40,4,2),KONECT(200,2),PAR(350)
      COMMON OUTPUT(200),OUTOLD(200),OLDIN(200)
      COMMON T(20),TOLD(20),TC(20),DTDT(20),DTDTO(20)
      COMMON/STRT/SYR,SMN,SDA,SHR
      COMMON/LAB1/KARTYP(40,4),IUSEG(40)
      COMMON/FILES/INDATA,KLMIT,KOUT,LUTERM
      COMMON/STRGE/STORX(4,20),XOLD(4,20),ISU(4)
      COMMON/GHMN/TAIOLD,TCOLD,WAIOLD
      COMMON/CGHMN/GHOLD(8),MMAX,BR,GS(3),GSOLD(3),GSUM(4),TD,
     1    BRF(4,24),TGOOLD(26),TGSOLD(26),GHTIME
      COMMON/NSR/TCOV,TSUR
      COMMON/LB/LABEL(2,40,5),LABU(5)
      COMMON/CNTRL/CD(10,8)
      COMMON/MSTOR/TMS(10,5),TIMMST,MITER
      DIMENSION ITITLE(40),NAME(10),NAMEO(10),IBUF(15),KWRT(60,2)
C
C       INITIALIZE ERROR TOLERANCE FOR CONVERGENCE, MAX. NO. OF
C       ITERATIONS
      ETOL=.01
      ITMAX=20
C
C      INPUT FILE OF SIMULATION RUN PARAMETERS AND CHARACTERISTICS
      OPEN(INDATA,FILE='MEBDI',IOSTAT=IOS,ERR=52)
      GOTO 54
   52 WRITE(LUTERM,53) IOS
   53 FORMAT(" MEBDI OPEN ERROR = ",I4)
C     READ HEADING AND WEATHER AND OUTPUT FILE NAMES
   54 READ(INDATA,202)(ITITLE(I),I=1,40)
  202 FORMAT(40A2)
C       WEATHER DATA FILE NAME
      READ(INDATA,200)(NAME(I),I=1,10)
  200 FORMAT(10A2)
C       OUTPUT FILE NAME
      READ(INDATA,200)(NAMEO(I),I=1,10)
```

```
C      OPEN WEATHER DATA FILE
       OPEN(KLMIT,FILE=NAME,IOSTAT=IOS,ERR=55)
       GOTO 57
   55  WRITE(LUTERM,56) (NAME(I),I=1,10),IOS
   56  FORMAT(1H ,10A2,"  OPEN ERROR ",I4)
C      OPEN OUTPUT FILE OR DEVICE
   57  IF(NAMEO(1).EQ.KOUT) GOTO 60
       OPEN(KOUT,FILE=NAMEO,IOSTAT=IOS,ERR=58)
       GOTO 59
   58  WRITE(LUTERM,56) (NAMEO(I),I=1,10),IOS
C      ERASE ANY OUTPUT FROM A PREVIOUS RUN
   59  REWIND KOUT
   60  ENDFILE KOUT
C
C       WRITE HEADINGS
       WRITE(KOUT,201)
  201 FORMAT(20X,"MODULAR ENERGY BALANCE SIMULATION"/"  ")
       WRITE(KOUT,203)(ITITLE(I),I=1,40)
  203 FORMAT(1X,40A2)
C      GET TIME AND DATE OF RUN AND OUTPUT
       CALL FTIME(IBUF)
       WRITE(KOUT,204) (IBUF(I),I=1,15)
  204 FORMAT(" RUN AT ",15A2)
       WRITE(KOUT,190)(NAME(I),I=1,10)
  190 FORMAT(" WEATHER DATA FROM FILE ",10A2/)
C
C
C       GET YEAR(2 DIGIT), MONTH, DAY, AND HOUR (FRACTIONAL)
C       WHEN THE READER IS START PROVIDING DATA FROM THE KLMIT
C       FILE.  ALSO GET THE TIME INCREMENT
C       BETWEEN TIMES (HOURS), NO. OF TIMES SIMULATION IS TO BE DONE,
C       TIME OF FIRST TRACE, AND TIME TO STOP TRACE
       READ(INDATA,*) SYR,SMN,SDA,SHR,DELT,NTIMES,FTRACE,STRACE
C
C       GET NUMBER OF UNITS
       READ(INDATA,*) NUNITS
       WRITE(KOUT,205) SYR,SMN,SDA,SHR,DELT,NTIMES,FTRACE,STRACE,NUNITS
 205   FORMAT(" STARTING YR=",F3.0," MN=",F3.0," DY=",F3.0," HR=",F6.2//
     1          " INCREMENT  = ",F8.2," HOURS"/
     2          " NO. TIMES  = ",I8/
     3         " FIRST TRACE= ",F8.2," HOURS"/
     6         " LAST  TRACE= ",F8.2," HOURS"/
     4          " NO. UNITS  = ",I8/)
C
       DELT=DELT*3600.
       HDELT=DELT/2.
C
       NTGR=0
       NPRT=0
       KTROL=0
```

```
C
C       INITIALIZE LOWER SUBSCRIPT NUMBER FOR EACH UNIT IN THE
C       OUTPUT, KONECT, DTDT, AND PAR ARRAYS
        IOUTL=0
        IINL=0
        IDTDTL=0
        IPARL=0
C
        DO 999 IUNIT=1,NUNITS
C
C       GET THE TYPE NUMBER FOR EACH UNIT
        READ(INDATA,*) KTYPU(IUNIT)
        KTP=KTYPU(IUNIT)
      GOTO(1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,
     1     23,24) KTP
    1 WRITE(KOUT,501) IUNIT,KTP
  501 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," READER")
      GOTO 206
    2 WRITE(KOUT,502) IUNIT,KTP
  502 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," INTEGRATOR")
      GOTO 206
    3 WRITE(KOUT,503) IUNIT,KTP
  503 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," PRINTER")
      GOTO 206
    4 WRITE(KOUT,504) IUNIT,KTP
  504 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," THERMOSTAT")
      GOTO 206
    5 WRITE(KOUT,505) IUNIT,KTP
  505 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," GREENHOUSE")
      GOTO 206
    6 WRITE(KOUT,506) IUNIT,KTP
  506 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," PUMP OR FAN")
      GOTO 206
    7 WRITE(KOUT,507) IUNIT,KTP
  507 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," TEE")
      GOTO 206
    8 WRITE(KOUT,508) IUNIT,KTP
  508 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," SENSIBLE HEAT EXCHANGER")
      GOTO 206
    9 WRITE(KOUT,509) IUNIT,KTP
  509 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," LATENT AND SENSIBLE",
     1       " HEAT EXCHANGER")
      GOTO 206
   10 WRITE(KOUT,510) IUNIT,KTP
  510 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," FLAT PLATE SOLAR",
     1       " COLLECTOR")
      GOTO 206
   11 WRITE(KOUT,511) IUNIT,KTP
  511 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," FLUID STORAGE TANK")
      GOTO 206
```

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   12 WRITE(KOUT,512) IUNIT,KTP
  512 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," TIME FUNCTION")
      GOTO 206
   13 WRITE(KOUT,513) IUNIT,KTP
  513 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," RESERVOIR")
      GOTO 206
   14 WRITE(KOUT,514) IUNIT,KTP
  514 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," COMPLICATED GREENHOUSE")
      GOTO 206
   15 WRITE(KOUT,515) IUNIT,KTP
  515 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," SIMPLE GREENHOUSE")
      GOTO 206
   16 WRITE(KOUT,516) IUNIT,KTP
  516 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," HEATER")
      GOTO 206
   17 WRITE(KOUT,517) IUNIT,KTP
  517 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," NIGHT SKY RADIATOR")
      GOTO 206
   18 WRITE(KOUT,518) IUNIT,KTP
  518 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," EVAPORATIVE AIR COOLER")
      GOTO 206
   19 WRITE(KOUT,519) IUNIT,KTP
  519 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," ROCK BED STORAGE")
      GOTO 206
   20 WRITE(KOUT,520) IUNIT,KTP
  520 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," ARITHMETIC CALCULATOR")
      GOTO 206
   21 WRITE(KOUT,521) IUNIT,KTP
  521 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," ON-OFF THERMOSTAT")
      GOTO 206
   22 WRITE(KOUT,522) IUNIT,KTP
  522 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," MULTISTAGE THERMOSTAT")
      GOTO 206
   23 WRITE(KOUT,523) IUNIT,KTP
  523 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," CURTAIN HEAT EXCHANGER")
      GOTO 206
   24 WRITE(KOUT,524) IUNIT,KTP
  524 FORMAT(/" UNIT ",I2," IS A TYPE ",I2," PASSIVE STORAGE")
      GOTO 206
C
C        BYPASS THIS SECTION IF THE IUNIT TH UNIT HAS NO PARAMETERS
  206  IF(KARTYP(KTP,1).EQ.0) GOTO 107
C
C        TEST FOR DEVICES WHICH HAVE VARIABLE NUMBER OF PARAMETERS
C        FIRST PARAMETER MUST BE TOTAL NUMBER OF PARAMETERS AND BE ON
C        THE LINE BEFORE THE REST OF THE PARAMETERS
C        GH
       IF(KTP.EQ.5)  GOTO 236
C        TIMFN
       IF(KTP.EQ.12) GOTO 236
```

```
C        RSVOR
        IF(KTP.EQ.13) GOTO 236
C        ARITH
        IF(KTP.EQ.20) GOTO 236
C        MSTAT
        IF(KTP.EQ.22) GOTO 236
C
C        COMPUTE THE SUBSCRIPTS WHERE THE PARAMETERS FOR DEVICES WITH
C        CONSTANT NUMBER OF PARAMETERS WILL BE STORED.
        KSUBS(IUNIT,1,1)=IPARL+1
        KSUBS(IUNIT,1,2)=KSUBS(IUNIT,1,1)+KARTYP(KTP,1) -1
C        GET THE VALUES OF THE PARAMETERS FOR DEVICES WITH CONSTANT NO.
C       OF PARAMETERS
        IPARF=KSUBS(IUNIT,1,1)
        IPARL=KSUBS(IUNIT,1,2)
        READ(INDATA,*) (PAR(IPAR),IPAR=IPARF,IPARL)
        GOTO 235
C
C       HAVE A DEVICE WITH VARIABLE NO. OF PARAMETERS.
C       READ TOTAL NO. OF PARAMETERS
   236  READ(INDATA,*) NPARI
        PARI(1)=NPARI
C       READ THE REST OF THE PARAMETERS
        READ(INDATA,*)(PARI(IPAR),IPAR=2,NPARI)
C        COMPUTE THE SUBSRIPTS WHERE THESE PARAMETERS WILL BE STORED
        KSUBS(IUNIT,1,1)=IPARL+1
        KSUBS(IUNIT,1,2)=KSUBS(IUNIT,1,1) + NPARI -1
        KARTYP(KTP,1)=NPARI
C        STORE THESE PARAMETERS
        IPARF=KSUBS(IUNIT,1,1)
        IPARL=KSUBS(IUNIT,1,2)
        DO 237 IPAR=IPARF,IPARL
        PAR(IPAR)=PARI(IPAR-IPARF+1)
   237 CONTINUE
C
   235   WRITE(KOUT,229)
   229 FORMAT(" PARAMETERS  ")
        IL=IPARL-IPARF+1
        DO 230 I=1,IL
   230 PARI(I)=PAR(I+IPARF-1)
        WRITE(KOUT,209)(I,PARI(I),I=1,IL)

        GOTO 102
C
   107 KSUBS(IUNIT,1,1)=-1
        KSUBS(IUNIT,1,2)=-1
        WRITE(KOUT,229)
C
C         CHANGE KARTYP FOR TYPES OF DEVICES WITH VARIABLE CHARACTERISTICS
C         INTEGRATOR - VARIABLE NO. OF INS AND OUTS
```

```
  102 IF(KTP.EQ.2) KARTYP(2,2)=INT(PAR(IPARF) + .1)
      IF(KTP.EQ.2) KARTYP(2,3)=KARTYP(2,2)
C      PRINTER HAS VARIABLE N. OF INPUTS
      IF(KTP.EQ.3) KARTYP(3,2)=INT(PAR(IPARF) + .1)
C      GRNHS - VARIABLE NO. OF INPUTS, OUTPUTS, AND DERIVATIVES
      IF(KTP.EQ.5) KARTYP(5,2)=14 + INT(3.*PAR(IPARF+1) + .1)
      IF(KTP.EQ.5) KARTYP(5,4)=INT(PAR(IPARF+2) + .1)
      IF(KTP.EQ.5) KARTYP(5,3)=22+KARTYP(5,4)+INT(3.*PAR(IPARF+1)+.1)
C      TANK - VARIABLE NO. OF DERIVATIVES
      IF(KTP.EQ.11) KARTYP(11,4)=INT(PAR(IPARF) + .1)
C      RSVOR  -  NO. OF OUTPUTS IS 1 LESS THAN NO. OF PARAMETERS
      IF(KTP.EQ.13) KARTYP(13,3)=KARTYP(13,1) - 1
C      CGRNHS - VARIABLE NO. OF INPUTS, OUTPUTS
      IF(KTP.EQ.14) KARTYP(14,2)=21 + INT(3.*PAR(IPARF) + .1)
      IF(KTP.EQ.14) KARTYP(14,3)=46+INT(3.*PAR(IPARF)+.1)
C      SGRNHS - VARIABLE NO. OF INPUTS
      IF(KTP.EQ.15) KARTYP(15,2)=8 + INT(2.*PAR(IPARF) + .1)
C      ROCK - VARIABLE NO. OF OUTPUTS AND DERIVATIVES
      IF(KTP.EQ.19) KARTYP(19,4)=PAR(IPARF) + .1
      IF(KTP.EQ.19) KARTYP(19,3)=KARTYP(19,4) + 11
C      ARITH - VARIABLE NO. OF INPUTS
      IF(KTP.EQ.20) KARTYP(20,2)=PAR(IPARF+1) + .1
C      MSTAT - VARIABLE NO. OF OUTPUTS
      IF(KTP.EQ.22) KARTYP(22,3)=2*(KARTYP(22,1) - 2)
C
C
C             BYPASS THIS SECTION IF THE UNIT TH UNIT HAS NO INPUTS
      IF(KARTYP(KTP,2).EQ.0) GOTO 103
C
C
C      COMPUTE THE SUBSCRIPTS WHERE THE INPUT FOR IUNIT WILL BE STORED
      KSUBS(IUNIT,2,1)=IINL+1
      KSUBS(IUNIT,2,2)=KSUBS(IUNIT,2,1)+KARTYP(KTP,2) -1
C
C      GET THE UNIT NO.S AND THE OUTPUT NO.S OF THE OUTPUTS CONNECTED
C      TO THE INPUTS OF IUNIT
      IINF=KSUBS(IUNIT,2,1)
      IINL=KSUBS(IUNIT,2,2)
      READ(INDATA,*)(KONECT(IIN,1),KONECT(IIN,2),IIN=IINF,IINL)
      WRITE(KOUT,216)
  216 FORMAT(" INPUTS (INPUT NO., UNIT NO., OUTPUT NO.)")
      IL=IINL-IINF+1
      DO 220 I=1,IL
      DO 220 J=1,2
  220 KWRT(I,J)=KONECT(I+IINF-1,J)
      WRITE(KOUT,219)(I,KWRT(I,1),KWRT(I,2),I=1,IL)
  219 FORMAT((1H ,6(I6,I4,I3)))
      GOTO 121
  103 KSUBS(IUNIT,2,1)=-1
      KSUBS(IUNIT,2,2)= -1
```

```
      WRITE(KOUT,216)
C
C       BYPASS THIS OUTPUT PORTION IF THE IUNIT TH UNIT HAS NO OUTPUTS
  121 IF(KARTYP(KTP,3).EQ.0) GOTO 101
C
C      COMPUTE THE SUBSCRIPTS WHERE THE OUTPUT FROM IUNIT WILL BE STORED
      KSUBS(IUNIT,3,1)=IOUTL+1
      KSUBS(IUNIT,3,2)=KSUBS(IUNIT,3,1)+KARTYP(KTP,3)-1
C
C       GET THE INITIAL VALUES OF THE OUTPUTS
      IOUTF=KSUBS(IUNIT,3,1)
      IOUTL=KSUBS(IUNIT,3,2)
      READ(INDATA,*)(OUTPUT(IOUT),IOUT=IOUTF,IOUTL)
      WRITE(KOUT,208)
  208 FORMAT(" INITIAL OUTPUTS   ")
      IL=IOUTL-IOUTF+1
      DO 210 I=1,IL
  210 OUTI(I)=OUTPUT(I+IOUTF-1)
      WRITE(KOUT,209)(I,OUTI(I),I=1,IL)
  209 FORMAT((1H ,6(I3,E10.4)))
      GOTO 104
  101 KSUBS(IUNIT,3,1)=-1
      KSUBS(IUNIT,3,2)=-1
      WRITE(KOUT,208)
C
C       BYPASS THIS SECTION IF THE IUNIT TH UNIT HAS NO DERIVATIVES
  104 IF(KARTYP(KTP,4).EQ.0) GOTO 105
C
C       COMPUTE THE SUBSCRIPTS WHERE THE DERIVATIVES OF IUNIT
C       WILL BE STORED
      KSUBS(IUNIT,4,1)=IDTDTL+1
      KSUBS(IUNIT,4,2)=KSUBS(IUNIT,4,1)+KARTYP(KTP,4) -1
C
C       GET INITIAL VALUES OF THE DEPENDENT VARIABLE WHOSE DERIVATIVE
C       MUST BE EVALUATED
      IDTDTF=KSUBS(IUNIT,4,1)
      IDTDTL=KSUBS(IUNIT,4,2)
      READ(INDATA,*)(T(IDTDT),IDTDT=IDTDTF,IDTDTL)
      WRITE(KOUT,224)
  224 FORMAT(" INITIAL VALUES OF DEPENDENT VARIABLES  ")
      IL=IDTDTL-IDTDTF+1
      DO 225 I=1,IL
  225 TI(I)=T(I+IDTDTF-1)
      WRITE(KOUT,209)(I,TI(I),I=1,IL)
      GOTO 115
  105 KSUBS(IUNIT,4,1)=-1
      KSUBS(IUNIT,4,2)=-1
      WRITE(KOUT,224)
C
C       IF THE DEVICE IS A TYPE 2 INTEGRATOR, INITIALIZE UNIT NUMBER
```

```
  115 IF(KTP.NE.2) GOTO 129
       NTGR=NTGR+1
       ISU(NTGR)=PAR(IPARF+2) + .01
C
C        IF THE DEVICE IS A TYPE 3 PRINTER, READ LABELS
  129 IF(KTP.NE.3) GOTO 148
       NPRT=NPRT+1
       LMAX=PAR(IPARF) + .01
       LABU(NPRT)=PAR(IPARF+3) + .01
       READ(INDATA,130)((LABEL(J,I,NPRT),J=1,2),I=1,LMAX)
  130 FORMAT(20(2A2))
       WRITE(KOUT,131)((LABEL(J,I,NPRT),J=1,2),I=1,LMAX)
  131 FORMAT(1H ,20(2A2))
C
C      IF THE DEVICE IS A TYPE 4 THERMOSTAT, INITIALIZE THE UNIT NUMBERS
C        AND TIMES AND OUTPUTS IN THE CD ARRAY.
  148 IF(KTP.NE.4) GOTO 147
       KTROL=KTROL+1
       CD(KTROL,1)=PAR(IPARF+1)
       CD(KTROL,2)= - DELT/3600.
       CD(KTROL,3)=0.
       CD(KTROL,4)=OUTPUT(IOUTF)
       CD(KTROL,7)=0.
C
C      IF THE DEVICE IS TYPE 5 GREENHOUSE, INIT OLD AIR TEMP, COVER TEMP,
C        AND HUMIDITY RATIO VALUES
  147 IF(KTP.NE.5) GOTO 149
       TAIOLD=OUTPUT(IOUTF)
       WAIOLD=OUTPUT(IOUTF+1)
       TCOLD =OUTPUT(IOUTF+2)
C
C        IF THE DEVICE IS A TYPE 14 GREENHOUSE, INITALIZE
C        OUTSIDE COVER TEMP, INSIDE COVER TEMP, VETETATION TEMP,
C        SOIL SURFACE TEMP, CURTAIN HEAT EXCHANGER TEMP, AIR TEMP,
C        AIR HUMIDITY RATIO, SOIL STORAGE TEMP, AND TIME
  149   IF(KTP.NE.14) GOTO 170
       DO 151 I=1,8
  151   GHOLD(I)=OUTPUT(IOUTF+I-1)
       GHTIME=-DELT/3600.
C       GET AND WRITE SOIL RESPONSE FACTORS AND TEMPERATURE HISTORY
       READ(INDATA,*) MMAX,GS(1),GS(2)
       READ(INDATA,*) BR,TD,BRF(4,1)
       WRITE(KOUT,161) MMAX,GS(1),GS(2),BR,TD,BRF(4,1)
  161 FORMAT(" SOIL RESPONSE FACTORS AND TEMPERATURE HISTORY"/
     1      " MMAX=",I3,"  GOOLD =",E13.5,"  GSOOLD=",E13.5/
     2      "   BR=",E13.5,"  TD=",F7.2,"  B41=",F10.5/
     3      2X,"M",5X,"B1",8X,"B2",8X,"B3",5X,"TGO",4X,"TGS")
       READ(INDATA,*) M1,(BRF(I,1),I=1,3)
       WRITE(KOUT,164) M1,(BRF(I,1),I=1,3)
  164 FORMAT(1H ,I3,3F10.5,2F7.2)
```

```
      DO 165 M=2,MMAX
      MM1=M-1
      READ(INDATA,*) M1,(BRF(I,M),I=1,3),TGOOLD(MM1),TGSOLD(MM1)
      IF(M1.NE.M) WRITE(KOUT,163)
  163 FORMAT(" M SEQUENCE ERROR IN RESPONSE FACTOR TABLE")
      WRITE(KOUT,164) M1,(BRF(I,M),I=1,3),TGOOLD(MM1),TGSOLD(MM1)
  165 CONTINUE
C       COMPUTE REST OF B4M'S FOR SEMI-INFINITE REGION
      DO 168 M=2,MMAX
      XM=M
  168 BRF(4,M)=BRF(4,1)*(SQRT(XM)-2.*SQRT(XM-1.)+SQRT(XM-2.))
C
C       IF THE DEVICE IS TYPE 17 NIGHT SKY RADIATOR, THEN INITIALIZE
C       OLD VALUES OF COVER AND SURFACE TEMPERATURE
  170 IF(KTP.NE.17) GOTO 152
      TCOV=OUTPUT(IOUTF + 2)
      TSUR=OUTPUT(IOUTF + 3)
C
C       IF THE DEVICE IS A TYPE 22 MULTISTAGE THERMERMOSTAT, INITIALIZE
  152 IF(KTP.NE.22) GOTO 999
      TIMMST=-DELT/3600.
      NSETS=PAR(IPARF) - 1.99
      DO 150 IOUT=1,NSETS
      IT2=IOUT*2 - 1
      TMS(IOUT,1)=OUTPUT(IOUTF+IT2-1)
      TMS(IOUT,4)=0.
  150 CONTINUE
C
C
  999 CONTINUE
C
C
C       INITIALIZE
      NDTDTS=IDTDTL
      NOUTS=IOUTL
      DO 108 IDTDT=1,NDTDTS
  108 DTDT(IDTDT)=0.
      DO 109 IOUT=1,NOUTS
      OLDIN(IOUT)=0.
  109 OUTOLD(IOUT)=OUTPUT(IOUT)
C
C
      RETURN
      END
```

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PAGE   1   FTN.    OPTS:   LYI         10:51 AM  TUE., 30  NOV., 1982

COVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOV
      PROGRAM MEBV1(5)
      DIMENSION IPAR(5)
      CALL RMPAR(IPAR)
      INSTN=IPAR(1)
      GOTO INSTN
      END
```

```
COVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOV
C
      SUBROUTINE READR

C
C       TYPE 1
C
C              THIS SUBROUTINE READS WEATHER DATA INTO CORE FROM A DISK
C       FILE NAMED "MEBKLMT" AND OPENED TO THE NAME "KLMIT". THE FILE
C       SHOULD BE IN THE FORMAT OF THE OUTPUT FROM THE USWCL PROGRAM
C       FOR DECODING NATIONAL WEATHER SERVICE DATA.  THE FIRST FIELD
C       ON A DATA LINE SHOULD BE A TWO LETTER LOCATION IDENTIFIER.
C
C       THE OUTPUTS ARE:
C       1-YEAR(2 DIGIT) 2-MONTH, 3-DAY, 4-HOUR, 5-DEW POINT (C)
C       6-HUM RATIO (KG/KG), 7-WIND SPEED (M/S), 8-STATION PRESSURE(KPA)
C       9-DRY BULB (C), 10-WET BULB (C), 11-RELATIVE HUMIDITY (%),
C       12-TOTAL SOLAR RADIATION ON A HORIZONTAL SURFACE (W/M2),
C       13-DIFFUSE ON HORIZ (W/M2), 14-ANGLE OF INCIDENCE ON HORIZ(DEG),
C       15-TOTAL ON VERT (W/M2), 16-DIFFUSE ON VERT (W/M2), 17-ANGLE
C       OF IN ON VERT (DEG), 18-TOTAL OF SURFACE TILTED
C       AT LATITUDE + 10 FROM HORIZ (W/M2), 19-DIFFUSE OF TILTED (W/M2)
C       20-ANGLE OF IN ON TILTED (DEG), 21-THERMAL SKY RADIATION (W/M2),
C       22- 8-14 U SKY RADIATION (W/M2), 23-FRACTIONAL CLOUD COVER.
C
C              PROGRAMMED BY B. A. KIMBALL, U. S. WATER CONSERVATION
C       LABORATORY, PHOENIX, ARIZONA.  1979.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      COMMON/STRT/SYR,SMN,SDA,SHR
      COMMON/FILES/INDATA,KLMIT,KOUT,LUTERM
      DIMENSION LOC(1)
C
      IMAX=23
  2    READ(KLMIT,1) LOC(1), (OUTI(I),I=1,IMAX)
   1  FORMAT(A2,1X,3(F2.0,1X),F5.1,1X,F5.1,1X,F8.5,1X,F5.2,1X,F6.2,1X,
     1 2(F5.1,1X),F3.0,3(1X,F4.0,1X,F3.0,1X,F2.0),2(1X,F4.0),1X,F5.2)
C
C       IF THE TIME READ FROM THE KLMIT FILE IS BEFORE THE START TIME
C       THEN GO BACK AND READ AGAIN
      IF(OUTI(1)-SYR)2,3,10
  3    IF(OUTI(2)-SMN)2,4,10
  4    IF(OUTI(3)-SDA)2,5,10
 5    IF(OUTI(4)-SHR)2,10,10
C
 10    WRITE(LUTERM,11)(OUTI(I),I=1,4)
  11  FORMAT(1X,3F3.0,F6.2)
C
      RETURN
      END
```

```
C
      SUBROUTINE INGTR
C
C      TYPE2
C
C           THIS SUBROUTINE INTEGRATES WITH TIME THE VARIABLE GIVEN IN
C      XIN( ).  THE NUMBER OF VARIABLES MUST BE GIVEN IN PARI(1),
C      AND THE SIZE OF THE TIME STEP MUST BE GIVEN IN PARI(2).
C      THE OUTPUT CONSISTS OF THE INTEGRATED VALUES OF THE INPUTS
C      IN THE SAME ORDER.
C
C             PROGRAMMED BY B. A. KIMBALL, U. S. WATER CONSERVATION
C      LABORATORY, PHOENIX, ARIZONA.  1979.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      COMMON ETOL,ITMAX,NTIMES,FTRACE,STRACE,DELT,HDELT
      COMMON/STRGE/STORX(4,20),XOLD(4,20),ISU(4)
      COMMON/FILES/INDATA,KLMIT,KOUT,LUTERM
      IMAX=PARI(1) +.1
C
C      GET THE UNIT NUMBER AND FIND POSITIONS IN THE STORAGE AND
C      OLD X ARRAYS WHERE THE VALUES FOR THIS INTEGRATOR ARE
C      STORED
      NU=PARI(3) + .01
      L=0
   10 L=L+1
      IU=ISU(L)
      IF(IU.EQ.NU) GOTO 11
      GOTO 10
C      THIS IS THE L TH INTEGRATOR
C
   11 IF(TIME.EQ. 0.) GOTO 2
C
      DO 1 I=1,IMAX
C
C      UPDATE INTEGRATED VALUES IN STORAGE ARRAY IN LABELED COMMON
      STORX(L,I)=STORX(L,I) + (XIN(I)+XOLD(L,I))*HDELT
C
C      SAVE CURRENT X VALUES FOR NEXT TIME
      XOLD(L,I)=XIN(I)
C
C      RETURN INTEGRATED VALUES
      OUTI(I)=STORX(L,I)
    1 CONTINUE
C
C      CHECK IF THIS IS A RESET TIME
      CT=PARI(2)
      T=TIME
    6 IF(CT .GE. .999) GOTO 7
      CT=CT*100.
```

```
      T=T*100.
      GOTO 6
    7 R1=(T/CT)
      R2=INT(T + .001)/INT(CT + .001)
      IF(ABS(R1-R2) .GT. .999E-6) GOTO 4
C
      DO 5 I=1,IMAX
    5 STORX(L,I)=0.
C
    4 RETURN
C
C       FIRST TIME, INITIALIZE ACCUMULATOR AND OLD X VALUES
C
    2 DO 3 I=1,IMAX
      STORX(L,I)=0.
      OUTI(I)=STORX(L,I)
      XOLD(L,I)=XIN(I)
    3 CONTINUE
      RETURN
      END
```

```
C
      SUBROUTINE PRNTR
C
C      TYPE3
C
C             THIS SUBROUTINE PRINTS OUTPUT DATA.  THE DATA TO BE
C      PRINTED MUST BE GIVEN SEQUENTIALLY IN THE XIN( ) ARRAY.  THE
C      NUMBER OF INPUTS MUST BE GIVEN IN PARI(1).
C      PARI(2) IS THE DESIRED ELAPSED TIME BETWEEN PRINT-OUTS.
C
C             PROGRAMMED BY B. A. KIMBALL, U. S. WATER CONSERVATION
C      LABORATORY, PHOENIX, ARIZONA.  1979.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      COMMON/FILES/INDATA,KLMIT,KOUT,LUTERM
      COMMON/LB/LABEL(2,40,5),LABU(5)
C
C      CHECK IF THIS IS A PRINT-OUT TIME
      CT=PARI(2)
      T=TIME
    1 IF(CT .GE. .999) GOTO 2
      CT=CT*100.
      T=T*100.
      GOTO 1
    2 R1=(T/CT)
      R2=INT(T + .001)/INT(CT + .001)
      IF(ABS(R1-R2) .GT. .001) GOTO 10
C
      WRITE(KOUT,12) TIME
   12 FORMAT(" TIME = ",F8.2)
      IMAX=PARI(1) + .1
C
C      GET THE UNIT NUMBER AND FIND POSITION IN THE LABEL ARRAY WHERE
C      LABELS FOR THIS PRINTER ARE STORED.
      NU=PARI(4) + .01
      L=0
    3 L=L+1
      IU=LABU(L)
      IF(IU.EQ.NU) GOTO 4
      GOTO 3
C      THIS IS THE L TH PRINTER
C
C      SELECT THE FORMAT FOR PAGE WIDTH
    4 IF(PARI(3).GT. 80.1) GOTO 6
      WRITE(KOUT,5)((LABEL(J,I,L),J=1,2),XIN(I),I=1,IMAX)
    5 FORMAT(5(1X,2A2,E12.6))
      GOTO 10
C
    6 WRITE(KOUT,7)((LABEL(J,I,L),J=1,2),XIN(I),I=1,IMAX)
    7 FORMAT(8(1X,2A2,E12.6))
```

```
C
   10 RETURN
      END
```

```
C
      SUBROUTINE TSTAT
C
C      TYPE 4  THERMOSTAT
C
C             THIS SUBROUTINE COMPARES A TEMPERATURE (OR OTHER INPUT
C      VARIABLE) GIVEN IN XIN(1) WITH A SET POINT GIVEN IN PARI(1).
C      IT THEN COMPUTES A CONTROL VARIABLE WHOSE VALUE RANGES FROM
C      0. TO 1.  VALUES OF THE DEVIATION FROM SET POINT AND OF THE
C      CONTROL VARIABLE FROM PREVIOUS ITERATIONS ARE STORED IN THE
C      CD( , ) ARRAY IN LABELED COMMON.  USING THE CHANGE IN DEVIATION
C      FROM SET POINT WITH CHANGES IN VALUE OF THE CONTROL VARIABLE,
C      A NEWTON-TYPE ITERATION IS USED TO COMPUTE THE VALUE OF THE
C      CONTROL VARIABLE FROM VALUES USED IN PAST ITERATIONS.  IN ORDER
C      TO ACHIEVE STABILITY, HOWEVER, THE SIZE OF THE COMPUTED
C      CORRECTION STEPS IS ALTERNATED BETWEEN FULL STEPS AND 0.1 STEPS.
C
C             THE CODE FOR THE CD ARRAY IS:
C      CD(I,1) UNIT NUMBER.  THE PROGRAM STORES THE INFORMATION FOR
C             EACH TYPE 4 THERMOSTAT ON DIFFERENT ROWS OF THIS ARRAY
C             AS DETERMINED BY THE FIRST SUBSCRIPT. THE FIRST SUBSCRIPT
C             MUST BE DIMENSIONED LARGER THAN THE TOTAL NUMBER OF TYPE
C             4 THERMOSTATS IN USE AT ONE TIME.  THE UNIT NUMBER AS
C             THE FIRST ELEMENT FOR  THE SECOND SUBSCRIPT MUST BE
C             GIVEN IN PARI(2) AND IS USED TO DETERMINE WHICH ROW
C             IS USED FOR WHICH THERMOSTAT.
C      CD(I,2) TIME.  USED TO RESET STORED VALUES.
C      CD(I,3) ITERATION COUNTER.
C      CD(I,4) VALUE OF CONTROL VARIABLE FROM PREVIOUS ITERATION.
C      CD(I,5) VALUE OF DEVIATION FROM SET POINT (FUNCTION) FROM
C             PREVIOUS ITERATION.
C      CD(I,6) VALUE OF CONTROL VARIABLE FROM PREVIOUS PREVIOUS
C             ITERATION.
C      CD(I,7) LAST COMPUTED VALUE OF CHANGE IN DEVIATION FROM SET
C             POINT WITH CHANGE IN CONTROL VARIABLE.
C      CD(I,8) ACCUMULATED VALUES OF CONTROL VARIABLE
C
C             THE THERMOSTAT HAS TWO MODES.  MODE 1 IS THE MORE USUAL
C      ABSOLUTE CASE, AND MODE 2 IS THE DIFFERENTIAL CASE, WHEREBY THE
C      VALUE CONSIDERED TO BE THE INPUT VARIABLE IS THE DIFFERENCE
C      BETWEEN TWO INPUT VARIABLES GIVEN IN XIN(1) AND XIN(2).
C      THE MODE CHOICE IS GIVEN AS THE THIRD PARAMETER, PARI(3).
C
C             PROGRAMMED BY B. A. KIMBALL, U. S. WATER CONSERVATION
C      LABORATORY, PHOENIX, ARIZONA.  1979.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      COMMON ETOL,ITMAX,NTIMES,FTRACE,STRACE,DELT,HDELT
      COMMON/FILES/INDATA,KLMIT,KOUT,LUTERM
      COMMON/CNTRL/CD(10,8)
```

```
C
C       GET UNIT NUMBER AND FIND POSITION IN THE CD( ) ARRAY WHERE
C       DATA FOR THIS CONTROLLER  ARE STORED.
      NU=PARI(2) + .01
      I=0
    1 I=I+1
      ICD=CD(I,1) + .01
      IF(NU.EQ.ICD) GOTO 2
      GOTO 1
C       DATA STARTS IN I TH ROW
C
C       COMPUTE CURRENT FUNCTION VALUE
    2 MODE=PARI(3) + .01
      IF(MODE.EQ.1) T=XIN(1)
      IF(MODE.EQ.2) T=XIN(1)-XIN(2)
       F=T-PARI(1)
      CD(I,3)=CD(I,3) + 1.
C
C       CHECK IF THIS IS THE FIRST CALL TO THIS SR FOR THIS TIME-STEP
       IF(ABS(TIME-CD(I,2)) .LT. .001) GOTO 4
C
C       RESET TIME, ITERATION COUNTER, ACCUMULATOR
      CD(I,2)=TIME
      CD(I,3)=1.
      CD(I,8)=0.
      IF(TIME.GT. 0.) GOTO 4
C
C       IF THIS IS FIRST SIMULATION TIME, CHANGE CONTROL VARIABLE
C       BY 10% IN DIRECTION TO MOVE F TOWARD 0.0
      OUTI(1)=CD(I,4) - 0.1*SIGN(1.,F)*CD(I,4)
      IF(OUTI(1) .GT. 1.) OUTI(1)=1.0
      IF(OUTI(1) .LT. 0.) OUTI(1)=0.0
      GOTO 10
C
C       CHECK NUMBER OF ITERATIONS TO SEE IF NEED TO FIX OUTPUT
    4 IT4MAX=ITMAX*3 + 1
      ICOM=CD(I,3) + .01
      IF(ICOM.LT. IT4MAX) GOTO 13
C       HAVE EXCESSIVE NUMBER OF ITERATIONS
      IF(ICOM.EQ. IT4MAX) OUTI(1)=CD(I,8)/(IT4MAX - 1)
      IF(ICOM.GT. IT4MAX) OUTI(1)=CD(I,4)
      GOTO 10
C
C       CALCULATE ALTERNATE FULL OR 0.1 STEP SIZE FOR PROPORTIONAL
C       CONTROL
   13 C1=INT(CD(I,3) + 1.0001)/2
      C2=CD(I,3)/2.
      CSTEP=1.0
      IF(ABS(C1-C2).LT. 0.01) CSTEP=0.1
C
```

```
C       CHECK FOR ZERO FUNCTION CHANGE
        DELF=F-CD(I,5)
        IF(ABS(DELF) .GT. 1.E-10) GOTO 5
C
C       CHECK ABSOLUTE FUNCTION VALUE
        IF(ABS(F).GT. .01) GOTO 7
C
C       FUNCTION ITSELF ZERO, SO KEEP SAME CONTROL VARIABLE VALUE
        OUTI(1)=CD(I,4)
        OUTI(2)= 1. - OUTI(1)
        IF(TIME.GE.FTRACE .AND. TIME.LE.STRACE)WRITE(KOUT,11)
     1     (J,CD(I,J),J=1,7)
   11 FORMAT(1H ,"CD="/,5(I4,E12.5))
C
        RETURN
C
C       FUNCTION NOT ZERO, USE OLD VALUE OF GRADIENT, TAKE SMALL STEP
    7   GRAD=CD(1,7)
        CSTEP= 0.1
C       IF HAVE ZERO GRADIENT, KEEP OLD VALUES
        OUTI(1)=CD(I,4)
        OUTI(2)=1. - OUTI(1)
        IF(ABS(GRAD).LE. 1.E-10) GOTO 10
        GOTO 32
C
C       CHECK FOR ZERO VARIABLE CHANGE
    5   DELX=CD(I,4)-CD(I,6)
        IF(ABS(DELX) .GT. 1.E-10) GOTO 8
C
C       CHECK IF HAVE MAX ON OR OFF
        IF(CD(I,4).EQ. 0.) GOTO 6
        IF(CD(I,4).EQ. 1.) GOTO 12
C
C       HAVE PROPORTIONAL CONTROL, BUT VARIABLE NOT CHANGING SO NUDGE
C       IT JUST A LITTLE BIT.
        OUTI(1)=0.99*CD(I,4)
        GOTO 10
C
C       COMPUTE GRADIENT
   8    GRAD=DELF/DELX
        CD(I,7)=GRAD
C
C       IF HAVE NEGATIVE GRADIENT NEED TO TURN MORE OFF IF F IS +
C       OR MORE ON IF F IS -
   32   IF(GRAD .GE. 0.) GOTO 9
        CHANGE=F/GRAD
C       REDUCE WILD CHANGES
        IF(CHANGE .GT. 0.2) CHANGE=0.2
        IF(CHANGE .LT. -.2) CHANGE=-.2
        OUTI(1)=CD(I,4) + CHANGE
```

```
      IF(OUTI(1) .GT. 1.0) OUTI(1)=1.0
      IF(OUTI(1) .LT. 0.0) OUTI(1)=0.0
      GOTO 10
C
C     COMPUTE NEW VALUE OF CONTROL VARIABLE FOR PROPORTIONAL CHANGE
    9 CHANGE= CSTEP*F/GRAD
C     REDUCE WILD CHANGES
      IF(CHANGE .GT. 0.2) CHANGE = 0.2
      IF(CHANGE .LT. -.2) CHANGE = -.2
      OUTI(1)=CD(I,4) - CHANGE
      IF(OUTI(1).GT. 1.) OUTI(1)=1.
      IF(OUTI(1).LT. 0.) OUTI(1)=0.
      GOTO 10
C
C      NO CHANGE IN X AND OUTPUT 1 OFF.  IF F HAS BECOME NEGATIVE, TURN
C      ON GENTLY.
    6 IF(F.GE. 0.) OUTI(1)=0.
      IF(F.LT. 0.) OUTI(1)=0.1
      GOTO 10
C
C      NO CHANGE IIN X AND OUTPUT 1 ON.  IF F HAS BECOME POSITIVE, TURN
C      OFF GENTLY.
   12 IF(F.LE. 0.) OUTI(1)=1.
      IF(F.GT. 0.) OUTI(1)=0.9
C
C      SHIFT DATA AND RETURN
   10 CD(I,6)=CD(I,4)
      CD(I,5)=F
      CD(I,4)=OUTI(1)
      CD(I,8)=CD(I,8) + OUTI(1)
      OUTI(2)= 1. - OUTI(1)
C
      IF(TIME.GE.FTRACE .AND. TIME.LE.STRACE) WRITE(KOUT,11)
     1    (J,CD(I,J),J=1,7)
C
      RETURN
      END
```

```
C
      SUBROUTINE FAN
C
C      TYPE 6 PUMP OR FAN
C
C             THE PUMP OR FAN IS MODELED BY SPECIFYING THE MAXIMUM FLOW
C      RATE THE PUMP OR FAN IS CAPABLE OF DELIVERING IN PARI(1).
C      THIS FLOW RATE IS THEN MULTIPLIED BY A  CONTROL VARIABLE
C      GIVEN IN XIN(4).  THE FLOW RATE IS OUTPUT IN OUTI(2).  FOR
C      CONTINUITY, WATER FLOWS INTO THE PUMP IN XIN(2), BUT THE
C      INFORMATION IS NOT USED.  TEMPERATURE INFORMATION FLOWS THROUGH
C      THE PUMP FROM XIN(1) TO OUTI(1), AND HUMITITY RATIO INFORMATION
C       FROM XIN(3) TO OUTI(3).
C
C             ADAPTED FROM KLEIN ET AL., "TRNSYS - A TRANSIENT
C      SIMULATION PROGRAM," UNIVERSITY OF WISCONSIN - MADISON,
C      ENGINEERING EXPERIMENT STATION REPORT 38, 1976.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      COMMON/FILES/INDATA,KLMIT,KOUT
      OUTI(1)=XIN(1)
      OUTI(2)=PARI(1)*XIN(4)
      OUTI(3)=XIN(3)
      RETURN
      END
```

```
C
      SUBROUTINE TEE
C
C      TYPE 7          TEE
C
C             THIS SUBROUTINE SIMULATES THE ACTION OF A TEE,
C      OUTLET MIXER, INLET MIXER, OR FLOW DIVERTER IN AN AIR
C      CONDITIONING DUCT.  IF THE ENTERING HUMIDITY RATIOS ARE SET
C      EQUAL TO ZERO, THE ROUTINE WILL ALSO SIMULATE THE ACTION OF A
C      TEE IN A LIQUID FLOW SYSTEM.  THE
C      FOUR MODES ARE AS FOLLOWS:
C
C      MODE 1 - TEE            TWO STREAMS CONVERGE INTO ONE.
C
C      MODE 2 - MIXER WITH   TWO STREAMS WHOSE MAXIMUM FLOW RATES ARE
C              KNOWN INLETS   GIVEN ARE MIXED PROPORTIONAL TO A
C                             CONTROL VARIABLE. (GAMMA = 1 GIVES STREAM 1
C
C      MODE 3 - MIXER WITH   THE FLOW RATE OF THE MIXTURE COMING OUT
C              KNOWN OUTLET   IS GIVEN AND THE FLOW RATES OF TWO INLET
C                             STREAMS ARE PROPORTIONED ACCORDING TO A
C                             CONTROL VARIABLE. (GAMMA = 1 GIVES STREAM O
C
C      MODE 4 - FLOW DIVERTER A STREAM IS SPLIT BETWEEN TWO DUCTS
C                             PROPORTIONAL TO A CONTROL VARIABLE.
C                             (GAMMA = 1 GIVES STREAM 1.)
C
C             PROGRAMMED BY B.A. KIMBALL, U.S. WATER CONSERVATION
C      LABORATORY, PHOENIX, ARIZONA.  1980.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
C
C      ENTHALPY FROM TEMPERATURE AND HUMIDITY RATIO
      EN(T,W)=1005.*T + W*(2468.E3 + 1859.*T)
C
      MODE=PARI(1) + .01
      GOTO(1,2,3,4),MODE
C
C      HAVE TEE.  INLET FLOW RATES AS GIVEN.
    1 F1=XIN(2)
      F2=XIN(5)
      FO=F1+F2
      IF(FO.GT. 1.E-6) GOTO 5
      IF(XIN(7).GT. 0.5) GOTO 6
      GOTO 10
C
C      HAVE OUTLET FLOW MIXER. GIVEN MAX INLET FLOW RATES MIXED
C      PROPORTIONALLY.
    2 F1=XIN(2)*XIN(7)
      F2=XIN(5)*(1.-XIN(7))
```

```
      FO=F1+F2
      IF(FO.GT. 1.E-6) GOTO 5
      IF(XIN(7).GT. 0.5) GOTO 6
      GOTO 10
C
C      HAVE INLET FLOW MIXER.  GIVEN OUTLET FLOW RATE AND INLET
C      FLOW RATES ARE PROPORTIONED.
    3 F1=XIN(2)*XIN(7)
      F2=XIN(2)-F1
      FO=F1+F2
      IF(FO.GT. 1.E-6) GOTO 5
      IF(XIN(7).GT. 0.5) GOTO 6
      GOTO 10
C
C      COMPUTE OUTLET FLOW RATE, HUMIDITY RATIO, AND TEMP
    5 T1=XIN(1)
      W1=XIN(3)
      T2=XIN(4)
      W2=XIN(6)
      WO=(F1*W1 + F2*W2)/FO
      E1=EN(T1,W1)
      E2=EN(T2,W2)
      EO=(F1*E1 + F2*E2)/FO
      T3=(EO - 2.468E6*WO)/(1005. + 1859.*WO)
      OUTI(1)=T3
      OUTI(2)=FO
      OUTI(3)=WO
      OUTI(4)=0.
      OUTI(5)=0.
      OUTI(6)=0.
      IF(MODE.EQ.3) GOTO 8
      RETURN
C
C      GET INLET FLOW RATES FOR OUTPUTS
    8 OUTI(2)=F1
      OUTI(5)=F2
      RETURN
C
C      HAVE ZERO FLOW RATES BUT MORE CALL FOR STREAM 1
    6 DO 7 I=1,3
      OUTI(I)=XIN(I)
    7 OUTI(I+3)=0.
      IF(MODE.EQ. 3) GOTO 8
      RETURN
C
C     HAVE ZERO FLOW RATES BUT MORE CALL FOR STREAM 2
   10 DO 11 I=1,3
      OUTI(I)=XIN(I+3)
   11 OUTI(I+3)=0.
      IF(MODE.EQ.3) GOTO 8
```

```
      RETURN
C
C       FLOW DIVERTER
    4 OUTI(1)=XIN(1)
      OUTI(2)=XIN(2)*XIN(7)
      OUTI(3)=XIN(3)
      OUTI(4)=XIN(1)
      OUTI(5)=XIN(2)*(1.-XIN(7))
      OUTI(6)=XIN(3)
C
      RETURN
      END
```

```
C
      SUBROUTINE LXR
C
C             TYPE 9 LATENT AND SENSIBLE HEAT EXCHANGER
C
C             THIS SUBROUTINE SIMULATES THE PERFORMANCE OF DIRECT
C      CONTACT HEAT EXCHANGERS SUCH AS COOLING TOWERS, AS WELL AS
C      INDIRECT EXCHANGERS SUCH AS COILS THAT MAY BE WET OR DRY
C      DEPENDING ON INTERFACE CONDITIONS AND DEW POINT.
C
C             THE COMPUTATIONAL METHOD USED IS  TO DIVIDE THE EXCHANGER
C      INTO SEGMENTS AND THEN TO STEP THROUGH SEGMENT BY SEGMENT.  IN EAC
C      SEGMENT THE INTERFACE TEMPERATURE AND HUMIDITY RATIO ARE COMPUTED
C      FROM AN ENERGY BALANCE EQUATING THE HEAT TRANSFER IN THE WATER
C      TO THE SENSIBLE AND LATENT HEAT TRANSFER IN THE AIR.  AFTER THE
C      INTERFACE CONDITIONS ARE OBTAINED, THE CHANGE IN AIR TEMPERATURE
C      AND HUMIDITY RATIO AND WATER TEMPERATURE THROUGH THE SEGMENT
C      ARE COMPUTED.
C
C             THE ABOVE PROCEDURE IS DIRECTLY APPLICABLE TO PARALLEL
C      FLOW.  FOR COUNTER FLOW, A GUESS IS MADE OF THE WATER TEMPERATURE
C      WHERE THE AIR ENTERS, AND A NEWTON ITERATION IS USED TO IMPROVE
C      THE GUESS UNTIL THE COMPUTED WATER TEMPERATURE AI AIR EXIT EQUALS
C      THE ACTUAL WATER TEMPERATURE THERE.
C
C             PROGRAMMED BY B. A. KIMBALL, U. S. WATER CONSERVATION
C      LABORATORY, PHOENIX, ARIZONA.  1979.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      COMMON ETOL,ITMAX,NTIMES,FTRACE,STRACE,DELT,HDELT
      COMMON/FILES/INDATA,KLMIT,KOUT,LUTERM
      REAL LACT,KDAM
C
C      * PSYCHROMETRIC FUNCTIONS FROM  T IN DEG C AND P IN KPA *
C
C      SATURATION VAPOR PRESSURE (KPA) TETENS EQN
      SVP(T)=0.61078*EXP(17.2694*T/(T+237.3))
C      SATURATION HUMIDITY RATIO (KG H2O/KG AIR)
      SHR(T,P)=0.62198/((P/SVP(T))-1.)
C
C      * PARAMETERS *
C
C      SET MODE = 1 FOR DIRECT CONTACT; =2 FOR DIRECT CONTACT ONLY
C      WHEN INTERFACE TEMP IS BELOW DEW POINT.
      MODE=PARI(1) + .1
C
C      FLOW DIRECTION (+1 FOR PARALLEL; -1 FOR COUNTER FLOW)
      DIRFL=PARI(2)
C
C      CROSS-SECTIONAL AREA (M2)
```

```
      ACS=PARI(3)
C
C      ACTUAL LENGTH (M)
      LACT=PARI(4)
C
C       HEAT CAPACITY OF LIQUID (J/(KG*C))
      C=PARI(5)
C
C      * INPUTS *
C
C      GET AVERAGE FLOW RATES (KG/S) AND SCALE UP TO ACTUAL FLOW RATES
C      THROUGH THE EXCHANGER FOR THE FRACTION OF TIME IT IS ON
      FA=XIN(2)
      FL=XIN(5)
      GAM=XIN(8)
      IF(GAM.LT. 1.E-6) GOTO 20
      FA=FA/GAM
      FL=FL/GAM
      IF(FA.LT. 1.E-6 .OR. FL.LT. 1.E-6) GOTO 20
C
C      INLET AIR TEMPERATURE (C), HUMIDITY RATIO (KG/KG)
      TA1=XIN(1)
      GA = FA/ACS
      WA1=XIN(3)
C
C      INLET LIQUID TEMP (C)
      TWIN=XIN(4)
      GL=FL/ACS
C
C      BAROMETRIC PRESSURE (KPA)
      PRSR=XIN(6)
C
C      INITIALIZE FOG FLAG
      IFOG=+1
C
C
C      COMPUTE MASS AND HEAT TRANSFER COEFFICIENTS, METAL RESISTANCE
      KDAM = PARI(6)*(GA**PARI(7))*(GL**PARI(8))
      HAAH = KDAM*(1005. + 1859.*WA1)
      HLAH = PARI(9)*(GA**PARI(10))*(GL**PARI(11))
      RL   = 1./HLAH
      RM   = PARI(12)
      U    = 1./(RL + RM)
C
C
C      IF HAVE PARALLEL FLOW, CAN STEP THROUGH ONCE AND RETURN
      IF(DIRFL.NE.1.) GOTO 2
      TW1=TWIN
      ASSIGN 1 TO JBACK
      GOTO 700
```

```
     1 TWOUT =TW2
       GOTO 15
C
C        HAVE COUNTER FLOW. INITIALIZE OLD WATER TEMPS, FUNCTION VALUE
     2 TWOLR=(TWIN+TA1)/2.
       TWOLD=TWOLR + 0.1
       TW1=TWOLR
       ASSIGN 3 TO JBACK
       GOTO 700
     3 FOLR=TW2-TWIN
C
       IF(TIME.GE.FTRACE .AND. TIME.LE.STRACE) WRITE(KOUT,11)
    11 FORMAT(" ITTW",4X,"TWNEW",8X,
     1   "TWOLD",8X,"TWOLR",8X,"FOLD",9X,"FOLR")
C
C        START OF ITERATION LOOP FOR COMPUTING WATER TEMPERATURE
       ITTW=0
     4 ITTW=ITTW + 1
C
C        COMPUTE OLD FUNCTION VALUE
       TW1=TWOLD
       ASSIGN 5 TO JBACK
       GOTO 700
     5 FOLD=TW2-TWIN
C
C        NEW WATER TEMP ESTIMATE
       IF(ABS(FOLD-FOLR).LT. 1.E-10) GOTO 6
       TWNEW=TWOLD - FOLD*(TWOLD-TWOLR)/(FOLD-FOLR)
C
       IF(TIME.GE.FTRACE .AND. TIME.LE.STRACE) WRITE(KOUT,12) ITTW,
     1     TWNEW,TWOLD,TWOLR,FOLD,FOLR
    12 FORMAT(1H ,I3,5E13.5)
C
C        TEST FOR CONVERGENCE
       IF(ABS(TWNEW-TWOLD).LT. 0.01) GOTO 8
       IF(ITTW.GT.20) GOTO 6
C
C        CONVERGENCE NOT ATTAINED, GO BACK FOR ANOTHER ITERATION
       TWOLR=TWOLD
       TWOLD=TWNEW
       FOLR=FOLD
       GOTO 4
C
C        CONVERGENCE NOT ATTAINED, WRITE ERROR MESSAGE AND CONTINUE
     6 WRITE(KOUT,7) TIME,ITTW,TWOLR,TWOLD,FOLR,FOLD
     7 FORMAT(" *** WARNING - CONVERGENCE NOT ATTAINED IN LXCHNR ***"/
     1     "      TIME = ",E13.6,"     NO. OF ITERATIONS = ",I3/
     2     "     TWOLR = ",E13.6,"  TWOLD = ",E13.6/
     3     "      FOLR = ",E13.6,"   FOLD = ",E13.6)
C
```

```
C        CONVERGENCE OBTAINED
    8 TWOUT=TW1
C
   15 IF(IFOG .EQ. -1) WRITE(KOUT,9)
    9 FORMAT("  FOG ENCOUNTERED IN LXCHNR")
C
C        * OUTPUTS SCALED TO AVERAGE TIME OF OPERATION *
C
C        AIR EXIT TEMPERATURE (C)
       OUTI(1)=TA1 + GAM*(TA2-TA1)
C
C        AIR FLOW RATE
       OUTI(2)=XIN(2)
C
C        AIR EXIT HUMIDITY RATIO
       OUTI(3)=WA1 + GAM*(WA2-WA1)
C
C        LIQUID TEMPERATURE OUT (C)
       OUTI(4)=TWIN + GAM*(TWOUT-TWIN)
C
C        LIQUID FLOW RATE
       OUTI(5)=XIN(5)
C
C        TOTAL HEAT TRANSFER RATE FROM WATER TO AIR (+) OR AIR TO WATER (-)
C        (J/S)
       OUTI(6)=(TWIN-TWOUT)*C*FL*GAM
C
C        RATE EVAPORATION (+) OR CONDENSATION (-) (KG/S)
       OUTI(7)=(WA2-WA1)*FA*GAM
C
       RETURN
C
C        HAVE ZERO FLOW RATES
   20 DO 21 I=1,5
   21 OUTI(I)=XIN(I)
       OUTI(6)=0.
       OUTI(7)=0.
       RETURN
C
C----------------------------------------------------------------------
C
  700   CONTINUE
C
C              ROUTINE FOR STEPPING THROUGH EXCHANGER WITH KNOWN AIR
C        ENTRANCE TEMPERATURE AND HUMIDITY RATIO.  WATER TEMPERATURE
C        AT THE AIR ENTRANCE MUST ALSO BE GIVEN.
C        TA1 - ENTERING AIR TEMP (C)
C        WA1 - ENTERING AIR HUMIDITY RATIO
C        TW1 - WATER TEMP AT AIR ENTRANCE
C        DIRFL - FLOW DIRECTION (+1 PARALLEL, -1 COUNTER)
```

```
C       LACT - LENGTH OF COLUMN (M)
C       U, KDAM, HAAH - TRANSFER COEFFICIENTS
C       C - LIQUID HEAT CAPACITY
C       MODE - 1 DIRECT CONTACT, 2 NON-CONTACT
C
C       TA2 - EXIT AIR TEMP
C       WA2 - EXIT AIR HUMIDITY RATIO
C       TW2 - WATER TEMP AT AIR EXIT
C
C       INITIALIZE NUMBER OF SEGMENTS AND INCREMENTAL LENGTH
      NLS=20
      DELL=LACT/FLOAT(NLS)
C
C       INITIALIZE CONDITIONS ENTERING FIRST SEGMENT
      TAJ=TA1
      WAJ=WA1
      TWJ=TW1
      TIOLD=TW1
C
      CA=KDAM*DELL/GA
      CL=U*DELL/(GL*C*DIRFL)
C
C       START LOOP FOR STEPPING THROUGH EXCHANGER
      DO 799 J=1,NLS
C
C       LATENT HEAT OF VAPORIZATION AND HUMID HEAT CAPACITY
      HVAP=2.501E6 - 2381.*TWJ
      CPM=1005. + 1859.*WAJ
      HK=HVAP*KDAM
C
C       START LOOP FOR COMPUTING INTERFACE TEMPERATURE
      ITER=0
  720 ITER=ITER + 1
C
C       COMPUTE OLD HUMIDITY RATIO AND SLOPE
      WSAT=SHR(TIOLD,PRSR)
      WIOLD=WSAT
      IF(MODE.EQ.2 .AND. WSAT.GT.WAJ) WIOLD=WAJ
      DWDT=0.
      IF(MODE.EQ.1 .OR. WSAT.LT.WAJ) DWDT =
     1    WSAT*(1. + WSAT/0.62198)*(4098.03/(TIOLD+237.3)**2)
C
C       COMPUTE ESTIMATE OF TINEW
      TINEW=U*TWJ + HAAH*TAJ + HK*DWDT*TIOLD - HK*(WIOLD-WAJ)
      TINEW=TINEW/(U + HAAH + HK*DWDT)
C
C       TEST FOR CONVERGENCE
      IF(ABS(TINEW-TIOLD) .LT. 0.01) GOTO 723
      IF(ITER.GT.ITMAX) GOTO 721
      TIOLD=TINEW
```

```
      GOTO 720
C
C       CONVERGENCE PROBLEMS
  721 WRITE(KOUT,722) TIME,J,ITER,TAJ,WAJ,TWJ,TIOLD,TINEW
  722 FORMAT(" WARNING - CONVERGENCE PROBLEM IN LXCHNR"/
     1      " TIME = ",E13.5,"   SEGMENT",I3,"   ITERATION",I3/
     2      " TAJ = ",E13.5,"   WAJ = ",E13.5,"   TWJ = ",E13.5/
     3      " TIOLD = ",E13.5,"    TINEW = ",E13.5)
C
C       CONVERGENCE ATTAINED
  723 WI=SHR(TINEW,PRSR)
      IF(MODE.EQ.2 .AND. WI.GT.WAJ) WI=WAJ
C
C       HAVE INTERFACE CONDITIONS.  COMPUTE CHANGES THROUGH THE SEGMENT.
      TAJP1=TAJ + CA*(TINEW-TAJ)
      WAJP1=WAJ + CA*(WI-WAJ)
      TWJP1=TWJ + CL*(TINEW-TWJ)
C
C       CHECK FOR FOG FORMATION, ADJUST IF NECESSARY
      WSAT=SHR(TAJP1,PRSR)
      IF(WAJP1.LE.WSAT) GOTO 724
      IFOG=-1
C     SEP84 BUG CORRECTION
      DWDT=WSAT*(1.+WSAT/0.62198)*(4098.03/(TAJP1+237.3)**2)
      CF=CPM/(HVAP*DWDT)
      WAJP1=(CF*WSAT + WAJP1)/(CF + 1.)
      TAJP1=TAJP1 + (WAJP1-WSAT)/DWDT
C
C       SET EXIT CONDITIONS FOR J TH SEGMENT TO BE THE ENTRANCE
C       CONDITIONS FOR THE NEXT SEGMENT
  724 TAJ=TAJP1
      WAJ=WAJP1
      TWJ=TWJP1
C
  799 CONTINUE
C
C       HAVE STEPPED THROUGH ENTIRE EXCHANGER. SET OUTPUT
C       VARIABLES.
      TA2=TAJP1
      WA2=WAJP1
      TW2=TWJP1
C
      GOTO JBACK
C
C----------------------------------------------------------------------
C
      END
```

```
C
      SUBROUTINE TANK
C
C      TYPE 11      WATER STORAGE TANK
C
C             THIS SUBROUTINE SIMULATES A STRATIFIED STORAGE TANK CONSIST
C      OF NEQ FULLY MIXED SECTIONS, THE VALUE OF NEQ BEING CHOSEN BY
C      THE USER.
C
C      REFERENCE:  "EXPERIMENTAL AND SIMULATED PERFORMANCE OF A CLOSED
C      LOOP SOLAR WATER HEATING SYSTEM" BY P.I. COOPER, S.A. KLEIN, AND
C      C.W.S. DIXON PRESENTED AT THE ISES MEETING IN AUGUST, 1975.
C
C      VOL     - TOTAL VOLUME OF TANK (M3)
C      NEQ     - NUMBER OF EQUAL VOLUME SECTIONS
C      CPF     - SPECIFIC HEAT OF FLUID IN TANK (J/KG C)
C      RHOF   - DENSITY OF TANK FLUID (KG/M3)
C      HIGH   - TANK HEIGHT (M)
C      U       - LOSS COEFFICIENT (W/M2 C)
C      FLWSS - FLOW RATE FROM HEAT SOURCE (KG/S)
C      TIN     - TEMPERATURE FROM HEAT SOURCE (C)
C      FLWLL - FLOW RATE TO LOAD (MAKEUP FLUID FLOW RATE) (KG/S)
C      TL     - TEMP OF FLUID REPLACING THAT EXTRACTED TO SUPPLY LOAD (C)
C      UA     - TANK HEAT LOSS COEFFICIET MULTIPLIED BY SURFACE AREA
C               (W/C)
C
C             ADAPTED FROM KLEIN ET AL., "TRNSYS - A TRANSIENT
C      SIMULATION PROGRAM," UNIVERSITY OF WISCONSIN - MADISON,
C      ENGINEERING EXPERIMENT STATION REPORT 38, 1976.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      COMMON ETOL,ITMAX,NTIMES,FTRACE,STRACE,DELT,HDELT
      COMMON/FILES/INDATA,KLMIT,KOUT,LUTERM
      DIMENSION S1(10),S2(10),XMIX(10),CC(10),CL(10)
      REAL MSCP
C
      NEQ=PARI(1) + .1
      XNEQ=NEQ
      VOL=PARI(2)
      HIGH=PARI(3)
      CPF=PARI(4)
      RHOF=PARI(5)
      U=PARI(6)
      TAVGO=PARI(7)
      QHE=PARI(8)
      LOC=PARI(9) + .1
      LOCT=PARI(10) + .1
      TSET=PARI(11)
      IETA=PARI(12) + .1
C
```

```
      MSCP=VOL*RHOF*CPF
      PI=3.14159
      DIA=SQRT((4.*VOL)/(PI*HIGH))
C
C      TANK LOSS COEFFICIENTS FOR SIDE SEGMENTS AND ENDS
      UAS=(PI*DIA*HIGH/XNEQ)*U
      UAE=(PI*(DIA**2)/4.)*U
C
      TIN=XIN(1)
      FLWSS=XIN(2)
      TL=XIN(3)
      FLWLL=XIN(4)
      TENV=XIN(5)
      QBOOST=QHE
C
C      CHECK EXTERNAL CONTROL
      IF(IETA.EQ.1) QBOOST=QHE*XIN(6)
C      CHECK INTERNAL THERMOSTAT CONTROL
      IF(TI(LOCT).GE.TSET+1.) GOTO 5
      IF(TI(LOCT).LE.TSET-1.) GOTO 6
C      INTERPOLATE W/I 2 DEG DEAD BAND
      GAMTS=(TI(LOCT)-TSET-1.)/2.
      GAMTS=GAMTS*3.14159-1.5708
      GAMTS=.5 + SIN(GAMTS)/2.
      GOTO 7
    5 GAMTS=0.
      GOTO 7
    6 GAMTS=1.
    7 QBOOST=QBOOST*GAMTS
C
      FLWS=FLWSS*CPF
      FLWL=FLWLL*CPF
      IF(NEQ.EQ.1) GOTO 300
      QENV=0.
      CC(1)=0.
      CL(1)=0.
      D1=ABS(TI(1)-TIN)
      K1=1
      D2=ABS(TI(1)-TL)
      K2=1
      DO 4 J=2,NEQ
      CC(J)=0.
      CL(J)=0.
      IF(ABS(TI(J)-TIN).GT.D1) GOTO 62
      K1=J
      D1=ABS(TI(J)-TIN)
   62 CONTINUE
      IF(ABS(TI(J)-TL).GT.D2) GOTO 4
      K2=J
      D2=ABS(TI(J)-TL)
```

```
    4 CONTINUE
      IF(TIN.GE.TI(1)) K1=1
      IF(TL.LE.TI(NEQ)) K2=NEQ
      IF(K1.EQ.NEQ) K1=NEQ-1
      IF(K2.EQ. 1) K2=2
      CC(K1)=1.
      CL(K2)=1.
      S1(1)=0.
      S2(NEQ+1)=0.
      DO 150 J=2,NEQ
      S1(J)=S1(J-1)+CC(J-1)
      K=NEQ+2-J
      S2(K)=S2(K+1)+CL(K)
  150 CONTINUE
      XMIX(1)=0.
      DO 151 J=2,NEQ
      XMIX(J)=S1(J)*FLWS-S2(J)*FLWL
  151 CONTINUE
      TAVG=0.
      DO 3 J=1,NEQ
      UA=UAS
      IF (J.EQ.1) UA=UA+UAE
      IF (J.EQ.NEQ) UA=UA + UAE
      DTDTI(J)=CC(J)*FLWS*(TIN-TI(J))
      DTDTI(J)=DTDTI(J) + CL(J)*FLWL*(TL-TI(J))
      IF(XMIX(J).GT.0.) DTDTI(J)=DTDTI(J) + XMIX(J)*(TI(J-1)-TI(J))
      K=J+1
      IF(K.GT.NEQ) GOTO 162
      IF(XMIX(K).LT.0.) DTDTI(J)=DTDTI(J) - XMIX(K)*(TI(J+1)-TI(J))
  162 DTDTI(J)=DTDTI(J) + UA*(TENV-TI(J))
      QENV=QENV - UA*(TENV-TI(J))
      TAVG=TAVG + TI(J)
    3 CONTINUE
      TAVG=TAVG/XNEQ
      QB=QBOOST/FLOAT(LOC)
      DO 11 J=1,NEQ
      QB1=QB
      IF(J.GT.LOC) QB1=0.
      DTDTI(J)=(DTDTI(J)+QB)/MSCP*XNEQ
      QTANK=FLWL*(TI(1)-TL)
   11 CONTINUE
  170 DELAU=(TAVG-TAVGO)*MSCP
C
C       TI(1) - TEMP FROM TOP TANK SECTION TO LOAD
C       FLWL   - FLOW RATE TO LOAD
C       TI(NEQ) - TEMP TO HEAT SOURCE
C       QENV   - ENERGY LOST TO SURROUNDINGS
        OUTI(1)=TI(NEQ)
      OUTI(2)=FLWSS
      OUTI(3)=TI(1)
```

```
      OUTI(4)=FLWLL
      OUTI(5)=QENV
      OUTI(6)=QTANK
      OUTI(7)=DELAU
      OUTI(8)=QBOOST
C
      RETURN
C
C       ONE NODE TANK EQUATIONS
  300 UA=UAS + 2.*UAE
      QENV=UA*(TI(1)-TENV)
      QTANK=FLWL*(TI(1)-TL)
      DTDTI(1)=(FLWS*(TIN-TI(1))-QTANK-QENV+QBOOST)/MSCP
      TAVG=TI(1)
      GOTO 170
      END
```

```
C
      SUBROUTINE RSVOR
C
C      TYPE 13        INFINITE VOLUME STORAGE RESERVOIR
C
C             THIS SIMPLE PROGRAM IS AN INFINITE SUPPLY OF CONSTANT
C      TEMPERATURE WATER OR WHATEVER.
C
C             THIS DEVICE CAN BE USED TO SET THE VALUES OF  VARIABLES
C      TO THE VALUES OF PARAMETERS WHICH DO NOT CHANGE DURING THE
C      COURSE OF A RUN.  THE TOTAL NUMBER OF PARAMETERS MUST BE PARI(1).
C      THE NUMBER OF OUTPUTS IS ONE LESS THAN THE NUMBER OF PARAMETERS.
C
C             PROGRAMMED BY B. A. KIMBALL, U. S. WATER CONSERVATION
C      LABORATORY, PHOENIX, ARIZONA.  1979.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      NP=PARI(1) + .1
      DO 1 I=1,NP
      OUTI(I)=PARI(I+1)
    1 CONTINUE
      RETURN
      END
```

```
C
      SUBROUTINE TIMFN
C
C       TYPE 12      TIME DEPENDENT FORCING-FUNCTION
C
C              THIS SUBROUTINE GENERATES TIME DEPENDENT DATA, SO THAT SOME
C       VARIABLE IS FORCED TO FOLLOW A FIXED COURSE WITH TIME.
C
C              PARI(1) MUST CONTAIN THE TOTAL NUMBER OF PARAMETERS.
C              PARI(2) MUST CONTAIN THE TIME, AND
C              PARI(3) MUST CONTAIN THE FUNCTION VALUE OF A FIRST DEFINING
C                       POINT.
C              PARI(4) AND PARI(5) SIMILARLY DEFINE A SECOND POINT.
C              PARI(2*I) AND PARI(2*I+1) SIMILARLY DEFIND ADDITIONAL
C              POINTS UP TO A TOTAL POSSIBLE OF 29.
C
C              THE ROUTINE WILL COMPUTE THE POSITION THE PRESENT TIME IS I
C       THE CYCLE UNDER THE ASSUMPTION THE CYCLE IS REPETITIVE.
C
C              TWO SUCCESSIVE POINTS CAN HAVE THE SAME TIME VALUE TO DEFIN
C       A STEP CHANGE.  IN THIS CASE THE FUNCTION VALUE OF THE FIRST
C       POINT GIVEN IN THE PARAMETER SEQUENCE WILL THE USED FOR
C       INTERPOLATING IF TIME .LE. THE TIME AT THE STEP AND VICE VERSA.
C
C              FOR A REPETITIVE CYCLE, THE FUNCTION VALUE FOR THE
C       FIRST POINT MUST EQUAL THE VALUE OF THE LAST POINT TO AVOID
C       A STEP CHANGE.
C
C              ADAPTED FROM KLEIN ET AL., "TRNSYS - A TRANSIENT
C       SIMULATION PROGRAM," UNIVERSITY OF WISCONSIN - MADISON,
C       ENGINEERING EXPERIMENT STATION REPORT 38, 1976.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      COMMON/FILES/INDATA,KLMIT,KOUT,LUTERM
C
      N=(INT(PARI(1) + .1) - 1)/2
      TO=PARI(2)
      TT=PARI(2*N)
      CT=TT-TO
      RTIME=TIME
C
C       TEST IF TIME IS BEFORE STARTING TIME FOR THE DEFINED CYCLE.
      IF(TIME.GE.TO) GOTO 3
C       ADD CYCLES TO TIME UNTIL IT IS W/I DEFINED RANGE.
      ICT=0
    1 ICT=ICT+1
      RTIME=RTIME+CT
      IF(RTIME.GE.TO) GOTO 5
      IF(ICT.GT.366) GOTO 2
      GOTO 1
```

```
C
C       WRITE ERROR MESSAGE
      2 WRITE(KOUT,8) TIME
      8 FORMAT(" *** ERROR TIMFN - UNREASONABLE TIME = ",E14.6)
        RETURN
C
C       TEST IF TIME IS AFTER TIME FOR DEFINED RANGE OR CYCLE.
      3 IF(TIME.LE.TT) GOTO 5
C       SUBTRACT CYCLES UNTIL TIME IS W/I DEFINED RANGE
        ICT=0
      4 ICT=ICT+1
        RTIME=RTIME-CT
        IF(RTIME.LE.TT) GOTO 5
        IF(ICT.GT.366) GO TO 2
        GOTO 4
C
C       FIND WHICH DEFINING POINTS RTIME LIES BETWEEN
      5 M=2
      6 M=M+2
        IF(RTIME.LE.PARI(M)) GOTO 7
        GOTO 6
C
C       HAVE TIME SPANNED BY DEFINING POINTS
      7 F1=PARI(M-1)
        F2=PARI(M+1)
        T1=PARI(M-2)
        T2=PARI(M)
C
C       COMPUTE FUNCTION VALUE USING LINEAR INTERPOLATION
        F=F1+ (F2-F1)*(RTIME-T1)/(T2-T1)
        OUTI(1)=F
        OUTI(2)=1. - F
        RETURN
        END
```

```
C
      SUBROUTINE HEATR
C
C             TYPE 16 HEATER OR FURNACE
C
C             THE HEATER IS MODELED BY SPECIFYING THE MAXIMUM
C      RATE OF SENSIBLE  ENERGY OUTPUT (WATTS) THE
C      HEATER IS CAPABLE OF DELIVERING IN PARI(1), AND THE MAXIMUM
C      RATE OF WATER VAPOR PRODUCTION (KG/S) IN PARI(3).
C      THE TEMPERATURE RISE THROUGH THE HEATER IS THE PRODUCT
C      OF THE CONTROL VARIABLE IN XIN(4) TIMES THE SENSIBLE
C      HEAT DIVIDED BY THE MAXIMUM FLOW RATE AND THE HEAT  CAPACITY OF
C      AIR.   THE HUMIDITY RATIO RISE IS THE PRODUCT OF
C      THE CONTROL VARIABLE AND WATER PRODUCTION RATE DIVIDED BY THE MAX
C      FLOW RATE.  AFTER
C      THE  CONTROL VARIABLE GOES TO ZERO, THE FLOW RATE IS SET EQUAL
C      TO ZERO ALSO, OTHERWISE IT FLOWS AT THE RATE SPECIFIED IN PARI(2).
C
C             PROGRAMMED BY B. A. KIMBALL, U. S. WATER CONSERVATION
C      LABORATORY, PHOENIX, ARIZONA.  1979.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      COMMON/FILES/INDATA,KLMIT,KOUT,LUTERM
      OUTI(1)=XIN(1) + XIN(4)*PARI(1)/(PARI(2)*(1005.+1859.*XIN(3)))
      OUTI(2)=PARI(2)
      IF(XIN(4).LT. 1.E-10) OUTI(2)=0.
      OUTI(3)=XIN(3) + XIN(4)*PARI(3)/(PARI(2))
      RETURN
      END
```

```
C
      SUBROUTINE COOLR
C
C             TYPE 18 EVAPORATIVE AIR COOLER
C
C             THIS SUBROUTINE SIMULATES THE PERFORMANCE OF AN EVAPORATIVE
C       AIR COOLER.  THE AIR FLOW COMING OUT IS THE PRODUCT OF THE
C       MAXIMUM FLOW RATE AND A CONTROL VARIABLE.
C
C             PROGRAMMED BY B. A. KIMBALL, U. S. WATER CONSERVATION
C       LABORATORY, PHOENIX, ARIZONA.  1979.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      COMMON/FILES/INDATA,KLMIT,KOUT,LUTERM
C
C       SATURATION VAPOR PRESSURE (KPA FROM C - TETENS EQN)
      SVP(T)=0.61078*EXP(17.2694*T/(T+237.3))
C
C       SATURATION HUMIDITY RATIO (KG/KG)
      SHR(T,P)=0.62198/((P/SVP(T)) - 1.)
C
C       HUMIDITY RATIO (KG/KG)
      HR(TD,TW,P)=(SHR(TW,P)*(2468.E3 - 2328.*TW) - 1005.*(TD-TW))/
     1    (2468.E3 + 1859.*TD - 4186.*TW)
C
C       MAX AIR FLOW RATE     SATURATION EFFICIENCY
      FMAX=PARI(1)
      SEFF=PARI(2)
C
C       INLET DRY BULB TEMP, WET BULB, BAROMETRIC PRESSURE
      TDI=XIN(1)
      TW=XIN(3)
      PRSR=XIN(5)
C
C       FLOW RATE
      OUTI(2)=FMAX*XIN(4)
C
      IF(XIN(4).GT. 0.) GOTO 1
      OUTI(1)=TDI
      OUTI(3)=0.
      OUTI(4)=0.
      RETURN
C
C       OUTPUT TEMPERATURE
    1 OUTI(1)= TDI - SEFF*(TDI-TW)
C
C       OUTPUT HUMIDITY RATIO
      WO=HR(OUTI(1),TW,PRSR)
      OUTI(3)=WO
C
```

```
C       EVAPORATION RATE (KG/S)
      WI=HR(TDI,TW,PRSR)
      OUTI(4)=OUTI(2)*(WO-WI)
C
      RETURN
      END
```

```
C
      SUBROUTINE ARITH
C
C      TYPE 20 ARITHMETIC OPERATOR
C
C             THIS SUBROUTNE PERFORMES ARITHMETIC OPERATIONS
C      ON TWO OR MORE INPUTS AS SPECIFIED BY THE PARAMETERS.
C      NP   = NUMBER OF INSTRUCTIONS = NUMBER OF PARAMETERS - 2
C      NI   = NUMBER OF INPUTS
C      NSTK = STACK INDEX
C      J    = INSTRUCTION (PARAMETER) INDEX
C      K    = INPUT INDEX
C      IOP  = OPERATION CODE
C
C             ADAPTED FROM KLEIN ET AL., "TRNSYS - A TRANSIENT
C      SIMULATION PROGRAM," UNIVERSITY OF WISCONSIN, MADISON,
C      ENGINEERING EXPERIMENT STATION REPORT 38, 1976.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      COMMON FILES/FILES/INDATA,KLMIT,KOUT,LUTERM
      DIMENSION STACK(10)
C
C      GET NUMBER OF ARITHMETIC PARAMETERS
      NP=PARI(1) - 1.99
      IF(NP.LT.1) GOTO 99
C
C      GET FIRST OPERATING CODE
      IOP=PARI(3) + SIGN(.01,PARI(3))
C
C      CHECK MODE OF OPERATION
      IF(IOP.LE.0) GOTO 300
C
C      HAVE MODE A: SINGLE OPERATION
      STACK(1)=XIN(1)
      STACK(2)=XIN(2)
      ISTK=2
      J=1
      IF(NP.NE.1) GOTO 99
      GOTO 400
C
C      HAVE MODE B: MULTIPLE OPERATIONS
  300 NI=PARI(2) + .01
      ISTK=0
      K=0
      J=0
C
C      START OF LOOP FOR STEPPING THROUGH THE INSTRUCTIONS GIVEN
C      BY THE PARAMETERS.
C      FIRST, CHECK IF HAVE COMPLETED THE REQUIRED NO. OF INSTRUCTIONS.
   30 IF(J.GE.NP) GOTO 40
```

```
      J=J+1
C
C      GET NEXT OPERATION CODE. GOTO APPROPRIATE STATEMENTS
      JP2=J+2
      IOP=PARI(JP2) + SIGN(.01,PARI(JP2))
  400 IF(IOP.LT.-1 .OR. IOP.GT.10) GOTO 99
      IP2=IOP+2
      GOTO (9,10,11,12,13,14,15,16,17,18,19,20),IP2
C
C      CODE IS -1; GET VALUE OF NEXT PARAMETER AND PLACE ON
C      STACK AS A CONSTANT.
    9 ISTK=ISTK+1
      IF(ISTK.GT.10) GOTO 99
      IF (J.GE.NP) GOTO 99
      J=J+1
      STACK(ISTK)=PARI(J+2)
      GOTO 30
C
C      CODE IS 0; PUT NEXT INPUT ON STACK
   10 ISTK=ISTK+1
      IF(ISTK.GT.10) GOTO 99
      IF(K.GE.NI) GOTO 99
      K=K+1
      STACK(ISTK)=XIN(K)
      GOTO 30
C
C      CODE IS 1; MULTIPLY.
   11 ISTK=ISTK-1
      IF(ISTK.LT.1) GOTO 99
      STACK(ISTK)=STACK(ISTK)*STACK(ISTK+1)
      GOTO 30
C
C      CODE IS 2; DIVIDE.
   12 ISTK=ISTK-1
      IF(ISTK.LT.1) GOTO 99
      IF(STACK(ISTK+1).EQ. 0.) GOTO 97
      STACK(ISTK)=STACK(ISTK)/STACK(ISTK+1)
      GOTO 30
C
C      CODE IS 3; ADD.
   13 ISTK=ISTK-1
      IF(ISTK.LT.1) GOTO 99
      STACK(ISTK)=STACK(ISTK)+STACK(ISTK+1)
      GOTO 30
C
C      CODE IS 4; SUBTRACT.
   14 ISTK=ISTK-1
      IF(ISTK.LT.1) GOTO 99
      STACK(ISTK)=STACK(ISTK)-STACK(ISTK+1)
      GOTO 30
```

```
C
C         CODE IS 5; EXPOENTIATE.
   15 ISTK=ISTK-1
      IF(ISTK.LT.1) GOTO 99
      STACK(ISTK)=STACK(ISTK)**STACK(ISTK+1)
      GOTO 30
C
C         CODE IS 6; TAKE LOG10
   16 STACK(ISTK)=ALOG10(STACK(ISTK))
      GOTO 30
C
C         CODE IS 7; NEGATE.
   17 STACK(ISTK)=-STACK(ISTK)
      GOTO 30
C
C         CODE IS 8; CHANGE NEGATIVE NUMBER TO ZERO.
   18 IF(STACK(ISTK).LT. 0.) STACK(ISTK)=0.
      GOTO 30
C
C         CODE IS 9; LOGICAL OR SO CHOOSE LARGER
 19       ISTK=ISTK-1
      IF(ISTK.LT.1) GOTO 99
      IF(STACK(ISTK+1).GT.STACK(ISTK)) STACK(ISTK)=STACK(ISTK+1)
      GOTO 30
C
C         CODE IS 10; LOGICAL AND SO CHOOSE SMALLER
 20       ISTK=ISTK-1
      IF(ISTK.LT.1) GOTO 99
      IF(STACK(ISTK+1).LT.STACK(ISTK)) STACK(ISTK)=STACK(ISTK+1)
      GOTO 30
C
C         HAVE REACHED BOTTOM OF STACK; GET OUTPUT AND RETURN.
   40 IF(ISTK.NE. 1) GOTO 99
      OUTI(1)=STACK(1)
      OUTI(2)=1. - OUTI(1)
      RETURN
C
C         WRITE ERROR MESSAGES
   99 WRITE(KOUT,98)
   98 FORMAT(" ERROR IN THE INSTRUCTIONS TO ARITH.  CHECK PARAMETERS"/
     1         " MAXIMUM NUMBER OF INSTRUCTIONS IS 10.")
      STOP
   97 WRITE(KOUT,96) TIME,(XIN(I),I=1,NI)
   96 FORMAT(" DIVISION BY ZERO IN ARITH AT TIME = ",F8.2/
     1     " INPUTS WERE: ",30E13.5)
      STOP
      END
```

```
C
      SUBROUTINE OSTAT
C
C      TYPE 21 ON-OFF THERMOSTAT
C
C             THIS THERMOSTAT IS A SIMPLE ON-OFF DEVICE.  WHEN THE
C      TEMPERATURE (OR OTHER VARIABLE) GIVEN IN XIN(1) IS LESS THAN A
C      SET POINT GIVEN IN PARI(1), THE VALUE OF OUTI(1) IS SET EQUAL
C      TO 1. AND THE VALUE OF OUTI(2) IS SET EQUAL TO 0.  WHEN THE
C      TEMPERATURE IS GREATER OR EQUAL TO THE SET POINT, THEY ARE
C      SET EQUAL TO 0. AND 1., RESPECTIVELY.
C             IF THE VALUE OF PARI(2) IS 2, A DIFFERENTIAL MOSE IS
C      USED AND THE SET POINT IS COMPARED TO XIN(1)-XIN(2).
C
C             PROGRAMMED BY B.A. KIMBALL, U.S. WATER CONSERVATION
C      LABORATORY, PHOENIX, ARIZONA.  MAY, 1980.
C
      COMMON TIME, XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      MODE=PARI(2) + .01
      T=XIN(1)
      IF(MODE.EQ.2) T=XIN(1)-XIN(2)
      OUTI(1)=0.
      IF(T.LT. PARI(1)) OUTI(1)=1.
      OUTI(2)=1.-OUTI(1)
      RETURN
      END
```

```
C
      SUBROUTINE MSTAT
C
C      TYPE 22 MULTISTAGE THERMOSTAT
C
C             THIS SUBROUTINE COMPARES A TEMPERATURE (OR OTHER INPUT
C      VARIABLE) GIVEN IN XIN(1) WITH A SERIES OF SET POINTS GIVEN IN
C      THE PARAMETERS.  IT THEN COMPUTES A CONTROL VARIABLE FOR EACH
C      STAGE WHOSE VALUE RANGES FROM 0. TO 1.  VALUES OF THE DEVIATIONS
C      FROM THE SET POINTS AND OF THE CONTROL VARIABLES FROM PREVIOUS
C      ITERATIONS ARE STORED IN THE TMS ARRAY IN LABELED COMMON.
C      USING THE CHANGE IN DEVIATION FROM SET POINT WITH CHANGES IN VALUE
C      OF THE CONTROL VARIABLE, A NEWTON-TYPE ITERATION IS USED TO COMPUT
C      THE VALUE OF THE CONTROL VARIABLES FROM VALUES USED IN PAST
C      ITERATIONS.  IN ORDER TO ACHIEVE STABILITY, HOWEVER,
C      THE SIZE OF THE COMPUTED CORRECTION STEPS IS ALTERNATED BETWEEN
C      FULL STEPS AND 0.1 STEPS.
C             ONLY ONE STAGE IS ALLOWED TO CONTROL PROPORTIONALLY AT A
C      TIME.  WHEN THE STAGES ON EACH SIDE OF THE INPUT TEMPERATURE
C      ARE BOTH TRYING TO CONTROL PROPORTIONALLY, CONTROL IS GIVEN
C      TO THE HIGHER STAGE IF THE HIGHER STAGE IS BELOW THE MASTER
C      SET POINT IN PARI(2), WHICH DIVIDES HEATING FROM COOLING.
C      CONVERSELY, CONTROL IS GIVEN TO THE LOWER STAGE IF THE HIGHER
C      STAGE IS ABOVE THE MASTER SET POINT.
C
C      THE CODES USED ARE:
C      MITER - ITERATION COUNTER
C      TIMMST- TIME USED TO RESET STORED VALUES
C      TMS(I, ) - ARRAY OF STORED VALUES WHERE I IS THE SUBSCRIPT
C                 FOR EACH STAGE OR SET POINT.
C      TMS(I,1) - VALUES OF CONTROL VARIABLES FROM PREVIOUS ITERATION.
C      TMS(I,2) - VALUES OF DEVIATIONS FROM SET POINTS (FUNCTIONS)
C                 FROM PREVIOUS ITERATION.
C      TMS(I,3) - VALUES OF CONTROL VARIABLES FROM PREVIOUS PREVIOUS
C                 ITERATION.
C      TMS(I,4) - LAST COMPUTED VALUES OF CHANGE DEVIATION FROM SET
C                 POINTS WITH CHANGE IN CONTROL VARIABLES (GRADIENTS).
C      TMS(I,5) - ACCUMULATED VALUES OF CONTROL VARIABLES.
C
C             PROGRAMMED BY B.A. KIMBALL, U.S. WATER CONSERVATION
C      LABORATORY, PHOENIX, ARIZONA.  MAY, 1980.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      COMMON ETOL,ITMAX,NTIMES,FTRACE,STRACE,DELT,HDELT
      COMMON/FILES/INDATA,KLMIT,KOUT,LUTERM
      COMMON/MSTOR/TMS(10,5),TIMMST,MITER
      DIMENSION TSET(10),F(10),GAM(10)
C
      NSETS=PARI(1) - 1.99
C
```

```
C        CHECK IF THIS IS THE FIRST CALL TO THIS SR FOR THIS TIME-STEP
C        IF SO, RESTET TIME, ITERATION COUNTER, ACCUMULATORS
      IF(ABS(TIME-TIMMST).LT. 0.01) GOTO 2
      TIMMST = TIME
      MITER = 0
      DO 1 I=1,NSETS
    1 TMS(I,5)=0.
C
C        INCREMENT ITERATION COUNTER, CHECK NUMBER
    2 MITER=MITER + 1
      IT22=ITMAX*3
      IF(MITER.LT.IT22) GOTO 7
C
C        HAVE EXCESSIVE ITERATIONS, FIX OUTPUTS
      IF(MITER.GT.IT22) GOTO 5
      DO 3 I=1,NSETS
    3 GAM(I)=TMS(I,5)/FLOAT(IT22)
      WRITE(KOUT,4)
    4 FORMAT(" WARNING: OUTPUTS FIXED BY MSTAT - EXCESSIVE ITERATIONS")
      GOTO 22
    5 DO 6 I=1,NSETS
    6 GAM(I)=TMS(I,1)
      GOTO 22
C
C        CALCULATE ALTERNATE FULL OR 0.1 STEP SIZE FOR PROPORTIONAL CONTROL
    7 C1=MITER/2
      C2=FLOAT(MITER)/2.
      CSTEP=1.0
      IF(ABS(C1-C2).LT. 0.01) CSTEP=0.1
C
C        GET THE INPUT TEMPERATURE, SET POINTS, NEW FUNCTION VALUES
      T=XIN(1)
      DO 8 I=1,NSETS
      TSET(I)=PARI(I+2)
    8 F(I)=T-TSET(I)
      TMAS=PARI(2)
C
C        START LOOP FOR CALCULATING NEW CONTROL VARIABLES FOR EACH STAGE.
      DO 99 ISET=1,NSETS
C
C        IF THIS IS FIRST SIMULATION TIME, CHANGE CONTROL VARIABLES BY
C        10% IN DIRECTION TO MOVE F TOWARD 0.
      IF(TIME.GT. 0.) GOTO 9
      IF(MITER.GT.1) GOTO 9
      GAM(ISET)=TMS(ISET,1) - 0.1*SIGN(1.,F(ISET))*TMS(ISET,1)
      IF(GAM(ISET).GT. 1.) GAM(ISET)=1.
      IF(GAM(ISET).LT. 0.) GAM(ISET)=0.
      GOTO 99
C
    9 SIZE=CSTEP
```

```
C
C        CHECK FOR ZERO FUNCTION CHANGE
       DELF=F(ISET)-TMS(ISET,2)
       IF(ABS(DELF).GT. 1.E-10) GOTO 11
C
C        CHECK ABSOLUTE FUNCTION VALUE
       IF(ABS(F(ISET)) .GT. 1.E-4) GOTO 10
C
C        FUNCTION ITSELF ZERO, GO KEEP SAME CONTROL VARIABLE VALUE
       GAM(ISET)=TMS(ISET,1)
       GOTO 99
C
C     HAVE DELF ZERO, BUT FUNCTION NOT ZERO
C      USE OLD VALUE OF GRADIENT, TAKE SMALL STEP
   10 GRAD=TMS(ISET,4)
       SIZE=0.1
C      IF GRADIENT ALSO IS ZERO, KEEP OLD VALUE OF CONTROL VARIABLE
       GAM(ISET)=TMS(ISET,1)
       IF(ABS(GRAD).LT. 1.E-10) GOTO 99
       GOTO 32
C
C        CHECK FOR ZERO VARIABLE CHANGE
   11 DELX=TMS(ISET,1)-TMS(ISET,3)
       IF(ABS(DELX).GT. 1.E-10) GOTO 12
C
C        CHECK IF MAX ON OR OFF
       IF(TMS(ISET,1).EQ. 0.) GOTO 14
       IF(TMS(ISET,1) .EQ. 1.) GOTO 15
C
C        HAVE PROPORTIONAL CONTROL, BUT VARIABLE NOT CHANGING SO NUDGE
C        IT A LITTLE BIT
       GAM(ISET)=0.99*TMS(ISET,1)
       GOTO 99
C
C        COMPUTE GRADIENT
   12 GRAD=DELF/DELX
       TMS(ISET,4)=GRAD
C
C        IF HAVE NEGATIVE GRADIENT NEED TO TURN MORE OFF IF F IS +
C        OR MORE ON IF F IS -
  32   IF(GRAD.GE. 0.) GOTO 13
       CHANGE=F(ISET)/GRAD
C      REDUCE WILD CHANGES
       IF(CHANGE .GT. 0.2) CHANGE=0.2
       IF(CHANGE .LT. -.2) CHANGE=-.2
       GAM(ISET)=TMS(ISET,1) + CHANGE
       IF(GAM(ISET) .GT. 1.) GAM(ISET)=1.
       IF(GAM(ISET) .LT. 0.) GAM(ISET)=0.
       GOTO 99
C
```

```
C        COMPUTE NEW VALUE OF CONTROL VARIABLE FOR PROPORTIONAL CHANGE
   13     CHANGE= SIZE*F(ISET)/GRAD
C       STOP WILD CHANGES
      IF(CHANGE .GT. 0.2) CHANGE =.2
      IF(CHANGE .LT. -.2) CHANGE =-.2
      GAM(ISET)=TMS(ISET,1) - CHANGE
       IF(GAM(ISET) .GT. 1.) GAM(ISET)=1.
       IF(GAM(ISET) .LT. 0.) GAM(ISET)=0.
       GOTO 99
C
C        NO CHANGE IN X AND CONTROL OFF. IF F HAS BECOME NEGATIVE, TURN
C        ON GENTLY.
   14 IF(F(ISET).GE. 0.) GAM(ISET)=0.
       IF(F(ISET).LT. 0.) GAM(ISET)=0.1
       GOTO 99
C
C        NO CHANGE IN X AND CONTROL ON.  IF F HAS BECOME POSITIVE, TURN
C        OFF GENTLY.
   15 IF(F(ISET).LE. 0.) GAM(ISET)=1.
       IF(F(ISET).GT. 0.) GAM(ISET)=0.9
C
   99 CONTINUE
C
C        MAKE SURE ONLY ONE STAGE IS CONTROLLING PROPORTIONALLY.
C        FIRST FIND WHICH SET POINT IS NEXT HIGHER THAN T
       IF(NSETS.EQ.1) GOTO 22
       NH=0
   16 NH=NH+1
       IF(NH.GT.NSETS) GOTO 17
       IF(T.LT.TSET(NH)) GOTO 17
       GOTO 16
C
C        SET ALL CONTROL VARIABLES MORE THAN 1 STAGE AWAY FROM T TO 0. OR 1
   17 NL=NH-1
       NLM1=NL-1
       IF(NLM1.LT.1) GOTO 19
       DO 18 I=1,NLM1
   18 GAM(I)=0.
   19 NHP1=NH+1
       IF(NHP1.GT. NSETS) GOTO 21
       DO 20 I=NHP1,NSETS
   20 GAM(I)=1.
C
C        T IS BETWEEN TWO SET POINTS. CHOOSE WHICH WILL HAVE CONTROL.
   21 IF(NL.LT.1 .OR. NH.GT.NSETS) GOTO 22
       IF(TSET(NL).LT.TMAS .AND. TSET(NH).LE.TMAS) GOTO 30
       IF(TSET(NL).GE.TMAS .AND. TSET(NH).GT.TMAS) GOTO 31
C
C        HAVE CASE WHERE BOTH HEATING AND COOLING ARE ADJACENT.
C        IF ONLY ONE OF STAGES IS CONTROLLING LET IT CONTINUE
```

```
C        TO CONTROL.
        IF(GAM(NL).EQ. 0. .OR. GAM(NH).EQ. 1.) GOTO 22
C        BOTH STAGES TRYING TO CONTROL.  GIVE CONTROL TO THE
C        LARGER, REMEMBERING THAT 1-GAM IS CONTROL VARIABLE FOR COOLING.
        OMG=1. - GAM(NH)
        IF(GAM(NL).GE.OMG) GAM(NH)=1.
        IF(GAM(NL).LT.OMG) GAM(NL)=0.
        GOTO 22
C
C        HAVE BOTH STAGES COOLER THAN TMAS.  TURN OFF COLDER STAGE
C        IF WARMER IS NOT ON COMPLETELY.
    30 IF(GAM(NH).LT. 1.)GAM(NL)=0.
        GOTO 22
C
C        HAVE BOTH STAGES WARMER THAN TMAS.  TURN OFF WARMER STAGE IF
C        COLDER STAGE NOT ON COMPLETELY
    31 IF(GAM(NL).GT. 0.) GAM(NH)=1.
C
C        SHIFT DATA, GET OUTPUTS AND RETURN
    22 DO 23 I=1,NSETS
        TMS(I,5)=TMS(I,5) + GAM(I)
        TMS(I,3)=TMS(I,1)
        TMS(I,2)=F(I)
        TMS(I,1)=GAM(I)
        II=2*I - 1
        OUTI(II)=GAM(I)
        OUTI(II+1)=1. - GAM(I)
    23 CONTINUE
C
        IF(TIME.LT.FTRACE .OR. TIME.GT.STRACE) GOTO 26
        WRITE(KOUT,24)
    24 FORMAT(" ISET",6X,"GAMA",10X,"F",9X,"GAMOLD",
      1     8X,"GRAD",8X,"SUMGAM")
        WRITE(KOUT,25) (I,(TMS(I,J),J=1,5),I=1,NSETS)
    25 FORMAT(1H ,I3,5E13.5)
C
    26 RETURN
        END
```

```
C
      SUBROUTINE CXR
C
C             TYPE 23 CURTAIN HEAT EXCHANGER
C
C             THIS SUBROUTINE SIMULATES THE PERFORMANCE OF A CURTAIN
C       HEAT EXCHANGER, WHICH CONSISTS OF A FILM OF PLASTIC DRAPED OVER A
C       WATER DISTRIBUTION PIPE.  HOT OR COLD WATER RUNS DOWN THE INSIDE
C       OF THE CURTAIN AND GAINS OR LOSES ENERGY TO THE AIR IN WHICH THE
C       CURTAIN IS LOCATED.  THE CURTAIN PHYSICALLY CAN EXCHANGE ENERGY
C       WITH THE AIR BY CONVECTION OF SENSIBLE AND LATENT HEAT AND WITH
C       OTHER SURFACES BY THERMAL RADIATION.  SOLAR RADIATION ABSORPTION I
C       ASSUMED NEGLIGIBLE.  THE ENERGY EXCHANGE BY THE SEVERAL
C       MECHANISMS IS ASSUMED TO GOVERENED BY A CONSTANT OVERALL HEAT TRAN
C       COEFFICIENT (PARAMETER 2).
C
C             THE SUBROUTINE COMPUTES THE OUTLET TEMPERATURE OF THE WATER
C       IT ALSO COMPUTES THE OUTLET TEMPERATURE AND FLOW RATE OF AN IMAGIN
C       STREAM OF AIR CARRYING THE ENERGY ADDED OR REMOVED BY THE
C       CURTAIN.
C
C             PROGRAMMED BY B. A. KIMBALL, U. S. WATER CONSERVATION
C       LABORATORY, PHOENIX, ARIZONA.  1980.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
C
C       PARAMETERS - AREA(M2), OVERALL HEAT TRANSFER COEF(W/(M2*C))
      A=PARI(1)
      U=PARI(2)
C
C       INPUTS - AIR TEMP(C), WATER TEMP(C) AND FLOW RATE(KG/S)
      TAI=XIN(1)
      TWI=XIN(4)
      FWI=XIN(5)
C
      R=(FWI*4190.)/(U*A)
C
C       OUTLET WATER TEMP
      TWO=(TWI*(R - .5) + TAI)/(R + .5)
C
C       RATE OF ENERGY TRANSFER (W)
      Q=FWI*4190*(TWO-TWI)
C
C       AIR TEMP OF IMAGINARY OUTLET WITH FLOW RATE OF 1 KG/S
      TAO=TAI - Q/1020.
C
C       OUTPUTS
      OUTI(1)=TAO
      OUTI(2)=1.
      OUTI(3)=XIN(3)
```

```
      OUTI(4)=TWO
      OUTI(5)=FWI
      OUTI(6)=Q
C
      RETURN
      END
```

```
C
      SUBROUTINE PSTOR
C
C             TYPE 24 PASSIVE STORAGE
C
C             THIS SUBROUTINE SIMULATES THE PERFORMANCE OF A STACK OF
C       WATER-FILLED BOTTLES OR OTHER SENSIBLE HEAT STORAGE MATERIAL
C       SUCH AS ROCKS IN THE SPACE WHOSE TEMPERATURE IS BEING MODIFIED.
C       INTERNAL TEMPERATURE GRADIENTS MUST BE INSIGNIFICANT, AND SOLAR
C       RADIATION ABSORPTION IS NOT CONSIDERED.  ENERGY EXCHANGE WITH AIR
C       IS PRESUMED TO OCCUR BY CONVECTION OF SENSIBLE AND LATENT HEAT
C       AND WITH OTHER SURFACES BY THERMAL RADIATION.  THE ENERGY EXCHANGE
C       BY THE SEVERAL MECHANISMS IS ASSUMED TO BE GOVERENED BY A CONSTANT
C       OVERALL HEAT TRANSFER COEFFICIENT (PARAMETER 2).
C
C             THE SUBROUTINE COMPUTES THE RATE OF TEMPERATURE CHANGE OF
C       THE STORAGE MATERIAL, AND RETURNS THIS TO THE MAIN PROGRAM FOR
C       INTEGRATION.  IT ALSO COMPUTES THE OUTLET TEMPERATURE AND FLOW
C       RATE OF AN IMAGINARY STREAM OF AIR CARRYING THE ENERGY ADDED OR
C       REMOVED FROM STORAGE.
C
C             PROGRAMMED BY B. A. KIMBALL, U. S. WATER CONSERVATION
C       LABORATORY, PHOENIX, ARIZONA.  1980.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
C
C       PARAMETERS - AREA(M2), OVERALL HEAT TRANSFER COEF(W/(M2*C)),
C                MASS OF STORAGE(KG), AND SPECIFIC HEAT OF STORAGE(J/((KG
      UA=PARI(1)*PARI(2)
      CM=PARI(3)*PARI(4)
C
C       INPUT AIR TEMP(C)
      TAI=XIN(1)
C
C       COMPUTE RATE OF ENERGY TRANSFER TO STORAGE (W)
      Q=UA*(TAI-TI(1))
C
C       RATE OF TEMP CHANGE OF STORAGE (C/S)
      DTDTI(1)=Q/CM
C
C       AIR TEMP OF IMAGINARY OUTLET WITH AIR FLOW RATE OF 1 KG/S
      TAO=TAI - Q/1020.
C
C       OUTPUTS
      OUTI(1)=TAO
      OUTI(2)=1.
      OUTI(3)=XIN(3)
      OUTI(4)=TI(1)
      OUTI(5)=Q
C
```

```
      RETURN
      END
```

```
PAGE   1   FTN.    OPTS:   LYI          10:55 AM  TUE., 30  NOV., 1982

COVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOV
      PROGRAM MEBV2(5)
      DIMENSION IPAR(5)
      CALL RMPAR(IPAR)
      INSTN=IPAR(1)
      GOTO INSTN
      END
```

```
COVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOV
C
      SUBROUTINE GH
C
C      TYPE 5          GREENHOUSE
C
C             THIS SUBROUTINE PERFORMS A COMPLETE ENERGY BALANCE
C      ON A GREENHOUSE AND COUPLES IT WITH A MOISTURE BALANCE OF THE
C      GREENHOUSE AIR.  AS A RESULT, THE GREENHOUSE AIR TEMPERATURE, COVE
C      TEMPERATURE AND HUMIDITY RATIO ARE SOLVED DIRECTLY, AND THE MOST
C      IMPORTANT SENSIBLE AND LATENT HEAT FLUXES ARE OBTAINED. EXTERNAL
C      DEVICES CAN ADD (OR REMOVE) ENERGY FROM THE GREENHOUSE AIR, COVER
C      AND ONE SOIL LAYER.
C
C             PROGRAMMED BY B. A. KIMBALL, U. S. WATER CONSERVATION
C      LABORATORY, PHOENIX, ARIZONA.  1980.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      COMMON/FILES/INDATA,KLMIT,KOUT,LUTERM
      COMMON/GHMN/TAIOLD,TCOLD,WAIOLD
      DIMENSION C(5),B(13),TX(4),WX(4),A(3,3),Y(3)
      REAL KV, LAI,K(5),KCF,KN,MX(4),MXC,MXG,KWF
C
C      *** FUNCTIONS ***
C
C      SATURATION VAPOR PRESSURE (TETENS) (KPA FROM T IN C)
      SVP(T)=0.61078*EXP(17.2694*T/(T+237.3))
C
C      SATURATION HUMIDITY RATIO (KG/KG FROM P IN KPA AND T IN C)
      SHRO(P,T)=.62198/((P/SVP(T))-1.)
C
C
C      SLOPE OF HUMIDITY RATIO VS TEMPERATURE CURVE
      SW(W,T)=W*(1. + W/0.62198)*4098.03/(T+237.3)**2
C
C      CONTROL VARIABLES FOR FLUID FLOW, COVER PROPERTIES,
C      POWERED CIRCULATION AND NATUTRAL VENTILATION
      GAMC=XIN(8)
      GAMP=XIN(9)
      GAMN=XIN(10)
      G1MF=1.-GAMF
      G1MC=1.-GAMC
      G1MP=1.-GAMP
C      *** PARAMETERS ***
C
C             TOTAL NUMBER OF PARAMETERS (50 + 2*NO. OF SOIL LAYERS)
      NP=PARI(1) + .1
C
C             TOTAL NUMBER OF EXTERNAL DEVICES  WITH
C             SENSIBLE AND LATENT HEAT FLUXES)
```

```
      JMAX=PARI(2) + .1
C
C             TOTAL NUMBER OF DERIVATIVES = NO. OF SOIL LAYERS
      MMAX=PARI(3) + .1
C
C       NO. OF SOIL LAYER THAT RECEIVES ENERGY FROM EXTERNAL DEVICE
      N=PARI(4)+.1
C
C             AREA OF COVER (M2)
      AC=PARI(5)
C
C       AREA OF SOIL (M2)
      AG=PARI(6)
C
C       AREA OF WALL WITH CONSTANT PROPERTIES(M2)
      AW=PARI(7)
C
C             VOLUME OF AIR IN GREENHOUSE (M3)
      VAI=PARI(8)
C
C
C       SPECIFIC HEAT OF FLUIDS THAT CARRY ENERGY TO COVER AN NTH SOIL
C       LAYER(J/KGC)
      CXC=PARI(9)
      CXG=PARI(10)
C
C       REFLECTANCE OF VEGETATION AND/OR SOIL FOR SOLAR RADIATION
      RHOV=PARI(11)
C
C       COEFFICIENTS FOR OUTSIDE HEAT TRANSFER COEFFICIENT
      B(1)=PARI(12)
      B(2)=PARI(13)
C
C       OVERALL HEAT TRANSFER COEFFICIENT FOR UNCHANGING WALL(W/M2 C)
      UW=PARI(14)*AW
C
C       TRANSMITTANCE AND ABSORBTANCE OF COVER FOR SOLAR RADIATION
      TAUS=G1MF*G1MC*PARI(15)+G1MF*GAMC*PARI(16)
     1 +GAMF*G1MC*PARI(17)+GAMF*GAMC*PARI(18)
      ALPH=G1MF*G1MC*PARI(19)+G1MF*GAMC*PARI(20)
     1 +GAMF*G1MC*PARI(21)+GAMF*GAMC*PARI(22)
C
C       INSIDE AIR HEAT TRANSFER COEFFICIENT(W/M2 C). REDUCE
      HAI=G1MP*PARI(23)+GAMP*PARI(24)
C       FLUID, INNER COVER, OUTER COVER THERMAL CONDUCTANCES(W/M2 C)
      HF=G1MF*PARI(25)+GAMF*PARI(26)
      HCO=G1MC*PARI(27)+GAMC*PARI(28)
      HCI=G1MC*PARI(29)+GAMC*PARI(40)
C
C       INFILTRATION AIR VELOCITY COEFFICIENTS
```

```
      B(3)=G1MC*PARI(31)+GAMC*PARI(32)
      B(4)=G1MC*PARI(33)+GAMC*PARI(34)
      B(5)=G1MC*G1MP*PARI(35)+G1MC*GAMP*PARI(36)
     1 +GAMC*G1MP*PARI(37)+GAMC*GAMP*PARI(38)
      B(6)=PARI(39)
      B(7)=PARI(80)
      B(8)=G1MP*PARI(41)+GAMP*PARI(42)
C
C      NATURAL VENTILATION, STOMATAL RESISTANCE COEFFICIENTS
      DO 10 I=9,13
   10 B(I)=PARI(I+34)
C
C      SOIL RESISTANCE(M2*2/KG)
      RG=PARI(48)
C
C             BOTTOM SOIL TEMP(C) AND CONDUCTANCE (W/M2 C)
      TI(MMAX+1)=PARI(49)
      K(MMAX+1)=(PARI(50))*AG
      IF(MMAX.EQ.0) GOTO 2
C
C      CONDUCTANCE (W/M2 C) AND HEAT CAPACITY (MJ/M2 C) OF SOIL LAYERS
      DO 1 M=1,MMAX
      K(M)=PARI(51 + (M-1)*2)*AG
      C(M)=PARI(52 + (M-1)*2)*1.E6*AG
    1 CONTINUE
    2 CONTINUE
C
C
C      *** INPUTS ***
C
C             TOTAL DOWNCOMING SOLAR RADIATION OUTSIDE (W/M2)
      SO=XIN(1)
C
C             OUTSIDE WIND SPEED (M/S)
      UAO=XIN(2)
C
C             OUTSIDE BAROMETRIC PRESSURE(KPA)
      PAO=XIN(3)
C
C             OUTSIDE AIR TEMP (C)
      TAO=XIN(4)
C
C             OUTSIDE HUMIDITY RATIO (KG/KG)
      WAO=XIN(5)
C
C      LEAF AREA INDEX
      LAI=XIN(6)
C
C
C      TEMPS, FLOW RATES FOR DEVICES THAT ADDS
```

```
C        ENERGY TO GREENHOUSE COVER AND SOIL LAYER
        TXC=XIN(11)
        MXC=XIN(12)*CXC*2.
        TXG=XIN(13)
        MXG=XIN(14)*CXG*2.
C
C               GET TEMP, FLOW RATE, AND HUMIDITY FROM EXTERNAL DEVICES
C        THAT EXCHANGE ENERGY WITH GREENHOUSE AIR
        SUMMX =0.
        SUMHX=0.
        SUMEX=0.
        IF(JMAX.EQ.0.) GOTO 4
        DO 3 J=1,JMAX
        JJ=15 + (J-1)*3
        TX(J)=XIN(JJ)
        MX(J)=XIN(JJ+1)
        WX(J)=XIN(JJ+2)
        SUMMX=SUMMX + MX(J)
        SUMHX=SUMHX + TX(J)*MX(J)
        SUMEX=SUMEX + WX(J)*MX(J)
    3 CONTINUE
    4 CONTINUE
C
C
C        HEAT CAPACITY OF AIR (J/(KG*C))
        CA=1005. + 1859.*WAIOLD
C
C        LATENT HEAT OF VAPORIZATION (J/KG)
        HVAP=2.501E6 - 2381.*TAIOLD
C        COMPUTE AIR DENSITY
        DA=PAO/(.287*(TAO+273.16))
C
C
C        SOLAR RADIATION ABSORBED IN GREENHOUSE, COVER
        SI=AG*SO*TAUS*(1.-RHOV)
        SC=AG*SO*ALPH
C
C        OVERALL HEAT TRANSFER COEFFICIENTS THROUGH COVER
        HAO=B(1)+B(2)*UAO
        UO=1./((1./HAO)+(1./HCO)+(1./HF))
        UO=UO*AC
        UI=1./((1./HAI)+(1./HCI)+(1./HF))
        UI=UI*AC
C
C        INFILTRATION COEFFICIENTS THROUGH COVER AND WALL
        DT=SQRT(ABS(TAIOLD-TAO))
        VCF=B(3)*UAO+B(4)*DT+B(5)
        HCF=VCF*CA*DA/1000.
        HCF=HCF*AC
        KCF=HCF*HVAP/CA
```

```
C
      VWF=B(6)*UAO+B(7)*DT+B(8)
      HWF=VWF*CA*DA/1000.
      HWF=HWF*AW
      KWF=HWF*HVAP/CA
C
C      NATURAL VENTILATION COEFFICIENTS
      VN=(B(9)*UAO + B(10)*DT)*GAMN
      HN=(VN/3600.)*VAI*DA*CA
      KN=HN*HVAP/CA
C
C      TRANSFER COEFFICIENT FOR EVAPOTRANSPIRATON (KG/(M2*S))
      RA=CA/HAI
C      LEAF STOMATAL RESISTANCE (M2 S/KG)
      SV=SO*TAUS
      RV=B(11) + B(12)/(B(13) + SV)
C      USE LEAF AREA INDEX TO CONVERT TO CROP RESISTANCE
      KV=LAI/(RA+RV) + 1./(RA+RG)
      KV=KV*AG*HVAP
C
C      GET COEFFICIENTS FOR LINEAR APPROXIMATION TO SATURATION HUMIDITY
C      RATIO VS TEMPERATURE CURVE
      WVOLD=SHRO(PAO,TAIOLD)
      SLP=SW(WVOLD,TAIOLD)
      TCEP=WVOLD - SLP*TAIOLD
C
C      COMPUTE THE COEFFICIENTS IN THE ENERGY AND MOISTURE BALANCE
C      EQUATIONS
      SUMUH=HCF+HN+UW+HWF
      SUMK=KCF+KN+KWF
C
      A(1,1)=CA*SUMMX + UI+SUMUH +K(1)
      A(1,2)= HVAP*SUMMX +SUMK
      A(1,3)=-UI
      Y(1)=SI + CA*SUMHX + HVAP*SUMEX + K(1)*TI(1)
     1         + TAO*SUMUH + WAO*SUMK
C
      A(2,1)=-KV*SLP
      A(2,2)= KV+ HVAP*SUMMX +SUMK
      Y(2)= KV*TCEP + HVAP*SUMEX + WAO*SUMK
C
      A(3,1)=-UI
      A(3,3)=MXC +UI +UO
      Y(3)=SC + MXC*TXC + UO*TAO
C
C      SOLVE USING CRAMERS RULE
      DET=A(1,1)*A(2,2)*A(3,3)-A(1,3)*A(2,2)*A(3,1)
     1      -A(1,2)*A(2,1)*A(3,3)
      IF(ABS(DET).GT.1.E-20) GO TO 105
C
```

```
C       WRITE ERROR MESSAGE
        WRITE(KOUT,101)
  101 FORMAT(" ***ZERO DETERMINANT IN GRNHS"/
     1        " AUGMENTED A MATRIX IS :")
        DO 102 I=1,3
 102    WRITE(KOUT,103) (A(I,J),J=1,3),Y(I)
 103    FORMAT(4E13.5)
C
C       USE OLD VALUES TO COMPUTE FLUXES
        TAI=TAIOLD
        WAI=WAIOLD
        TC=TCOLD
        GO TO 106
C
C       COMPUTE NEW VALUES OF TAI, WAI, TC
 105    D1=Y(1)*A(2,2)*A(3,3)-A(1,3)*A(2,2)*Y(3)-A(1,2)*Y(2)*A(3,3)
        TAI=D1/DET
C
        D2=A(1,1)*Y(2)*A(3,3)+A(1,3)*A(2,1)*Y(3)
     1      -A(1,3)*Y(2)*A(3,1)-Y(1)*A(2,1)*A(3,3)
        WAI=D2/DET
C
        D3=A(1,1)*A(2,2)*Y(3) + A(1,2)*Y(2) * A(3,1)
     1      - Y(1)*A(2,2)*A(3,1) - A(1,2)*A(2,1)*Y(3)
        TC=D3/DET
  106 CONTINUE
C
C       *** DTDT FOR SOIL TEMPERATURES ***
        XG=0.
         IF(MMAX.EQ.0) GOTO 16
        DTDTI(1)=(K(1)/C(1))*(TAI-TI(1))-(K(2)/C(1))*(TI(1)-TI(2))
        IF(MMAX.EQ.1) GOTO 17
        DO 15 M=2,MMAX
        DTDTI(M)=(K(M)/C(M))*(TI(M-1)-TI(M))-(K(M+1)/C(M))*
     1            (TI(M)-TI(M+1))
   15 CONTINUE
C       ADD EXTERNAL ENERGY TO NTH LAYER
   17 IF(N.LT.1 .OR. N.GT.MMAX) GO TO 16
        XG=MXG*(TXG - TI(N))
        DTDTI(N)=DTDTI(N) + XG/C(N)
   16 CONTINUE
C
C
C       *** OUTPUTS ***
C
C       INSIDE AIR TEMP(C), HUMIDITY RATIO(KG/KG) AND COVER TEMP(C)
        OUTI(1) =TAI
        OUTI(2)=WAI
        OUTI(3)=TC
C
```

```
C       SOLAR RADIATION ABSORBED BY GREENHOUSE AND COVER(W)
      OUTI(4)=SI
      OUTI(5)=SC
C
C       CONVECTION, THERMAL RADIATION FROM COVER TO OUTSIDE, INSIDE
C         TO COVER(W)
      OUTI(6)=UO*(TC - TAO)
      OUTI(7)=UI*(TAI - TC)
C
C       INFILTRATION OF SENSIBLE AND LATENT HEAT THROUGH COVER(W)
      OUTI(8)=HCF*(TAI - TAO)
      OUTI(9)=KCF*(WAI - WAO)
C
C       NATURAL VENTILATION OF SENSIBLE AND LATENT HEAT(W)
      OUTI(10)=HN*(TAI - TAO)
      OUTI(11)=KN*(WAI - WAO)
C
C       CONDUCTION AND INFILTRATION THROUGH UNCHANGING WALL(W)
      OUTI(12)=UW*(TAI - TAO)
      OUTI(13)=HWF*(TAI - TAO)
      OUTI(14)=KWF*(WAI - WAO)
C
C              SURFACE SOIL HEAT FLUX (W)
      OUTI(15)=K(1)*(TAI-TI(1))
C
C       EVAPOTRANSPIRATION (KG/S)
      WV=TCEP + SLP*TAI
      OUTI(16)=KV*(WV-WAI)/HVAP
C
C       SENSIBLE HEAT TO COVER (W), COVER FLUID EXIT TEMP(C),
C       AND FLOW RATES (KG/S)
      OUTI(17)=MXC * (TXC - TC)
      OUTI(18)=TC - (TXC - TC)
      OUTI(19)=XIN(12)
C
C       SENSIBLE HEAT ADDED TO NTH SOIL LAYER (W),SOIL FLUID EXIT
C       TEMP (C), AND FLOW RATE (KG/S)
      OUTI(20)= XG
      OUTI(21) = 0.
      IF(N.GE.1 .AND. N.LE.MMAX) OUTI(21)=TI(N) - (TXG-TI(N))
      OUTI(22)= XIN(14)
C
C       SURFACE SOIL HEAT FLUX(W)
C
C       SOIL TEMPERATURES (C)
      IF(MMAX.EQ.0) GO TO 20
       DO 19 M=1,MMAX
   19 OUTI(22+M)=TI(M)
C
C       SENSIBLE AND LATENT HEAT ADDED BY EXTERNAL DEVICES (W)
```

```
      IF(JMAX.EQ.0) GO TO 21
   20 DO 18 J=1,JMAX
      JO=23+MMAX + (J-1)*3
      OUTI(JO+2)=MX(J)*HVAP*(WX(J)-WAI)
      OUTI(JO+1)=MX(J)
      OUTI(JO)=MX(J)*(TX(J)-TAI)*CA
   18 CONTINUE
C
C
C       STORE THE NEW VALUES OF TAI AND WAI FOR THE NEXT CALL
   21 TAIOLD=TAI
      WAIOLD=WAI
      TCOLD=TC
C
       RETURN
      END
```

```
C
      SUBROUTINE SXR
C
C      TYPE8     SENSIBLE HEAT EXCHANGER W/O PHASE CHANGE
C
C      THIS ROUTINE  SIMULATES THE PERFORMANCE OF A SENSIBLE HEAT
C  EXCHANGER GIVING OUTLET TEMPS OF HOT AND COLD STREAMS.
C  MODE=1,2,3,4 SIGNIFY PARALLEL, COUNTERFLOW, CROSS FLOW AND CONSTANT
C  EFFECTIVNESS MODES.
C  IF MODE=4. THE HEAT EXCHANGER IS MODELED USING A CONSTANT
C  VALUE OF ITS EFFECTIVENESS, EFF, PROVIDED AS PARI(2) BASED UPON
C  THE HOT CAPACITANCE RATE, CH.
C  UA-OVERALL TRANSFER COEFF PER UNIT TEMP DIFFERENCE, CPH-SPECIFIC
C  HEAT OF HOT SIDE FLUID, CPC-SPECIFIC HEAT OF COLD SIDE FLUID
C  FLWH-HOT SIDE FLOW RATE, TCI-COLD SIDE INLET TEMP, FLWC-COLD SIDE
C  FLOW RATE
C             ADAPTED FROM KLEIN ET AL., "TRNSYS - A TRANSIENT
C      SIMULATION PROGRAM," UNIVERSITY OF WISCONSIN - MADISON,
C      ENGINEERING EXPERIMENT STATION REPORT 38, 1976.
C
      COMMON TIME, XIN(40), OUTI(80), TI(10), DTDTI(10), PARI(99)
      COMMON/FILES/INDATA, KLMIT, KOUT,LUTERM
      MODE=PARI(1)
      UA=PARI(2)
      CPH=PARI(3)
      CPC=PARI(4)
      IF (MODE.EQ.4) EFF=PARI(2)
      THI=XIN(1)
      TCI=XIN(3)
C
C      GET AVERAGE FLOW RATES (KG/S) AND SCALE UP TO ACTUAL FLOW RATES
C      THROUGH THE EXCHANGER FOR THE FRACTION OF TIME IT IS IN OPERATION.
      GAM=XIN(5)
      IF(GAM.LT. 1.E-6) GOTO 98
      FLWH=XIN(2)/GAM
      FLWC=XIN(4)/GAM
      IF(FLWH.LT. 1.E-6 .OR. FLWC.LT. 1.E-6) GOTO 98
C      CALCULATION OF MINIMUM AND MAXIMUM CAPACITY RATES
      CH=CPH*FLWH
      CC=CPC*FLWC
      CMAX=CC
      CMIN=CH
      IF(CH.GT.CC)CMAX=CH
      IF(CH.GT.CC)CMIN=CC
      IF (MODE.EQ.4) GO TO 13
      RAT=CMIN/CMAX
      UC=UA/CMIN
      EFF=1.0-EXP(-UC)
      IF((CMIN/CMAX).LE. 0.01) GOTO 14
      GO TO (10,11,12,13), MODE
```

```
C          PARALLEL FLOW
   10    EFF=(1.0-EXP(-UC*(1.0+RAT)))/(1.0+RAT)
         GO TO 14
C          COUNTER FLOW
   11    CONTINUE
         CHECK=ABS(1.0-RAT)
         IF(CHECK.LT.0.01) GO TO 20
         EFF=(1.0-EXP(-UC*(1.0-RAT)))/(1.0-RAT*EXP(-UC*(1.0-RAT)))
         GO TO 14
   12    CONTINUE
C    CROSSFLOW, HOT SIDE UNMIXED
         XP=1.0-EXP(-UC*RAT)
         EFF=1.0-EXP(-XP/RAT)
         IF(CMAX.EQ.CH) GO TO 14
         XP=1.0-EXP(-UC)
         EFF=(1.0-EXP(-XP*RAT))/RAT
         GO TO 14
   13    CONTINUE
         QMAX=CMIN*(THI-TCI)
         QT=EFF*QMAX
         THO=THI-QT/CH
         TCO=TCI+QT/CC
         GO TO 40
   20    EFF=UC/(UC+1.0)
   14    THO=THI-EFF*(CMIN/CH)*(THI-TCI)
         TCO=EFF*(CMIN/CC)*(THI-TCI)+TCI
         QT=EFF*CMIN*(THI-TCI)
C    THO-OUTLET TEMP ON HOT SIDE, TCO-OUTLET TEMP ON COLD SIDE,QT-
C    TOTAL INSTANTANEOUS ENERGY TRANSFER ACROSS EXCHANGER,
C    EFF-EFFECTIVENESS.
C          SCALE TO AVERAGE FLOW RATES
   40    OUTI(1)=THI + GAM*(THO-THI)
         OUTI(2)=XIN(2)
         OUTI(3)=TCI + GAM*(TCO-TCI)
         OUTI(4)=XIN(4)
         OUTI(5)=QT*GAM
         OUTI(6)=EFF
         RETURN
   98    OUTI(1)=THI
         OUTI(2)=XIN(2)
         OUTI(3)=TCI
         OUTI(4)=XIN(4)
         OUTI(5)=0.0
         OUTI(6)=0.0
         RETURN
         END
```

```
C
      SUBROUTINE CLECR
C
C      TYPE10          FLAT PLATE SOLAR COLLECTOR
C
C             THIS COMPONENT SUMULATES THE THERMAL PERFORMANCE OF A
C      FLAT-PLATE SOLAR COLLECTOR USING THE MODEL DEVELOPED BY
C      HOTTEL, WHILLIER, AND BLISS.
C
C      HR     - TOTAL RADIATION INCIDENT ON THE TILTED COLLECTOR SURFACE
C                       (W/M2)
C      QU     - THE USEFUL ENERGY COLLECTION RATE PER UNIT AREA (W/M2)
C      A       - COLLECTOR AREA (M2)
C      FP     - (F-PRIME) COLLECTOR GEOMETRY EFFICIENCY FACTOR
C      UL     - OVERALL ENERGY LOSS COEFFICIENT (W/M2 C)
C      TA     - AMBIENT TEMPERATURE (C)
C      TIN     - INLET FLUID TEMPERATURE (C)
C      TOUT   - OUTLET FLUID TEMPERATURE (C)
C      TM     - MEAN FLUID TEMPERATURE (C)
C      FLWRT - COLLECTOR FLUID FLOWRATE (KG/S)
C      CPF     - THERMAL CAPACITANCE OF THE COLLECTOR FLUID (J/KG C)
C      TAUALF - THE PRODUCT OF THE TRANSMITTANCE OF THE GLASS
C               AND THE ABSORPTANCE OF THE COLLECTOR PLATE SURFACE.
C               NOTE THAT DIFFUSE RADIATION IS TREATED AS IF IT STRIKES
C               THE COLLECTOR SURFACE AT 60 DEGREES.
C      GAM     - USED TO SCALE AVERAGE FLOW RATES TO ACTUAL FLOW RATES
C               FOR PORTION OF TIME COLLECTOR IS OPERATING
C
C
C             THIS PROGRAM HAS FOUR MODES OF OPERATION AS DETERMINED
C      FY THE VALUE OF MODE.
C             IF MODE=1, UL AND TAUALF ARE CONSTANTS
C             IF MODE=2,4,  UL IS CALCULATED AS A FUNCTION OF:
C
C      NG     - THE NUMBER OF GLASS COVERS
C      EP     - THE THERMAL EMITTANCE OF THE COLLECTOR PLATE SURFACE
C      UBE     - THE CONTRIBUTION TO UL DUE TO BOTTOM AND EDGE
C               LOSSES (W/M2-C)
C      ANGLE - THE TILT OF THE COLLECTOR WITH RESPECT TO HORIZONTAL (DEG)
C      WIND   - THE WINDSPEED (M/SEC)
C
C             IF MODE=3,4,  TAUALF IS CALCULATED AS A FUNCTION OF:
C
C      THETA1 - THE ANGLE OF INCIDENCE OF RADIATION ON THE COLLECTOR (DEG
C      ALF     - THE ABSORPTANCE OF THE COLLECTOR PLATE
C               SURFACE (CONTSTANT)
C      XKL     - PRODUCT OF THE EXTINCTION COEFFICIENT AND THE
C               THICKNESS OF EACH GLASS COVER
C      REFIND - THE REFRACTIVE INDEX OF THE GLASS
C      HBT     - THE INSTANTANEOUS BEAM RADIATION ON THE COLLECTOR SURFAC
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```
C                         (W/M2)
C          HDT     - THE INSTANTANEOUS DIFFUSE RADIATION ON THE
C                    COLLECTOR SURFACE (W/M2).
C
C                 ADAPTED FROM KLEIN ET AL., "TRNSYS - A TRANSIENT
C          SIMULATION PROGRAM," UNIVERSITY OF WISCONSIN - MADISON,
C          ENGINEERING EXPERIMENT STATION REPORT 38, 1976.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      COMMON/FILES/INDATA,KLMIT,KOUT,LUTERM
      DIMENSION ATR(3),BTR(3),CTR(3),TAU040(3)
      ASIN(X)=ATAN(X/SQRT(1.-X*X))
C
C      INITIALIZE CONSTANTS
      EG=.88
      PI=3.1415927
      SB=5.67E-08
      ATR(1)=-2.9868
      BTR(1)=-3.7360
      CTR(1)=4.3541
      ATR(2)=-1.4214
      BTR(2)=-5.7356
      CTR(2)=5.7723
      ATR(3)=-.74816
      BTR(3)=-6.5262
      CTR(3)=6.3769
      TAU040(1)=.92
      TAU040(2)=.845
      TAU040(3)=.785
      REFIND=1.526
C
      MODE=PARI(1)+.1
      A=PARI(2)
      FP=PARI(3)
      CPF=PARI(4)
      ALF=PARI(5)
      GOTO (21,22,23,24),MODE
   21 TAU=PARI(6)
      UL=PARI(7)
      TAUALF=TAU*ALF
      GOTO 71
   22 TAU=PARI(6)
      XNG=PARI(8)
      EP=PARI(9)
      UBE=PARI(10)
      ANGLE=PARI(11)
      NG=XNG+.1
      TAUALF=TAU*ALF
      GOTO 71
   23 UL=PARI(7)
```

```
      XNG=PARI(8)
      XKL=PARI(12)
      NG=XNG+.1
      GOTO 78
   24 XNG=PARI(8)
      EP=PARI(9)
      UBE=PARI(10)
      ANGLE=PARI(11)
      XKL=PARI(12)
      NG=XNG+.1
   78 CONTINUE
      TAU60=EXP(-1.21453*XKL*XNG)*(1.-EXP((ATR(NG)+(BTR(NG)+CTR(NG)
     1     *.5)*.5)*.5))
C       TAU60 IS THE TRANSMITTANCE OF THE GLASS COVER SYSTEM AT AN
C       ANGLE OF INCIDENCE OF 60 DEGREES, AS ASSUMED FOR DIFFUSE
C       RADIATION.  SEE HOTTEL AND WOERTZ.
   71 CONTINUE
      TIN=XIN(1)
      FLWRT=XIN(2)
      GAM=XIN(8)
      TA=XIN(3)
      GOTO (31,32,33,34), MODE
   31 CONTINUE
      HR=XIN(4)
      GOTO 72
   32 HR=XIN(4)
      WIND=XIN(6)
      GOTO 73
   33 HBT=XIN(4) - XIN(5)
      HDT=XIN(5)
      THETA1=XIN(7)
      GOTO 83
   34 HBT=XIN(4) - XIN(5)
      HDT=XIN(5)
      WIND=XIN(6)
      THETA1=XIN(7)
   83 CONTINUE
C
      HR=HBT+HDT
      TAU=0.
      IF(THETA1.GT.85.) GOTO 96
      IF(HR.LE.1.E-10) GOTO 96
      THETA1=THETA1*2.*PI/360.
      COSTH1=COS(THETA1)
      STH2=SIN(THETA1)/REFIND
      IF(ABS(STH2).GT. .99999) GOTO 25
      THETA2=ASIN(STH2)
      GOTO 26
   25 THETA2=PI/2.
   26 COSTH2=COS(THETA2)
```

```
      TAU=TAU040(NG)
      IF(COSTH1.GE. 0.766) GOTO 86
      TAU=1.-EXP((ATR(NG)+(BTR(NG)+CTR(NG)*COSTH1)*COSTH1)*COSTH1)
   86 CONTINUE
      TAU=HBT/HR*TAU*EXP(-XNG*XKL/COSTH2)
      TAU=TAU+HDT/HR * TAU60
C
   96 CONTINUE
      TAUALF=ALF*TAU
C
      GOTO(72,73,72,73),MODE
   73 CONTINUE
      ICT=0
      HWIND=5.7+3.8*WIND
      TM=TIN
   74 CONTINUE
      ICT=ICT+1
      IF(ICT.GT.2) GOTO 97
      TMC=TM+273.15
      TAC=TA+273.15
      IF(TMC.LE.TAC) TMC=TAC+1.
      F=(1.0-0.04*HWIND+5.0E-4*HWIND*HWIND)*(1.0+.091*XNG)
      C=365.9*(1.-.00883*ANGLE+.0001298*ANGLE*ANGLE)
      STF1=C/TMC*((TMC-TAC)/(XNG+F))**.33
      STF1=XNG/STF1 + 1./HWIND
      STF1=1./STF1
      STF2=1./(EP+.05*XNG*(1.-EP)) + (2.*XNG+F-1.)/EG-XNG
      STF2=SB*(TMC*TMC+TAC*TAC)*(TMC+TAC)/STF2
      UL=(STF1+STF2) + UBE
C       UL IS CALCULATED USING THE RELATION OF KLEIN
C
   72 CONTINUE
      IF(FLWRT) 4,4,3
    3 CONTINUE
C       SCALE FLOW RATE UP TO ACTUAL
      IF(GAM.LT. 1.E-3) GOTO 4
      AFLWRT=FLWRT/GAM
      FR=AFLWRT*CPF*(1.-EXP(-FP*UL*A/(AFLWRT*CPF)))/(A*UL)
      QU=GAM*A*FR*(HR*TAUALF - UL*(TIN-TA))
      TOUT=TIN + QU/(FLWRT*CPF)
      GOTO 5
    4 QU=0.
      TOUT=HR*TAUALF/UL + TA
    5 CONTINUE
      TM=(TIN+TOUT)/2.
      GOTO(97,74,97,74),MODE
   97 CONTINUE
      OUTI(1)=TOUT
      OUTI(2)=FLWRT
      OUTI(3)=QU
```

```
      OUTI(4)=UL
      OUTI(5)=TAUALF
      RETURN
      END
```

```
C
      SUBROUTINE SGH
C
C      TYPE 15 SIMPLIFIED GREENHOUSE
C
C             THIS SUBROUTINE DOES A SIMPLIFIED SUMULATION OF THE
C      ENERGY BALANCE OCCURING IN A GREENHOUSE.  THE SOLAR HEAT GAIN
C      PLUS THE SUM OF ANY EXTERNALLY SUPPLIED HEAT IS BALANCED
C      AGAINST THE HEAT REMOVED BY TRANS MISSION THROUGHT THE COVER
C      AND BY VENTILATION, EITHER NATURAL OR POWERED.  IF THE
C      VENTILATION IS POWERED, THE AIR CAN BE EVAPORATIVELY COOLED AS
C      IT ENTERS BY SPECIFYING AN APPROPRIATE SATURATION EFFICIENCY
C      OF THE ENTERING AIR.  THE WALL PROPERTIES CAN BE CHANGED BY
C      A CONTROL INPUT VARIABLE AS HAPPENS WHEN A CLOCK CONTROLS A THERMA
C      SCREEN.

C
C
C             PROGRAMMED BY B. A. KIMBALL, U. S. WATER CONSERVATION
C      LABORATORY, PHOENIX, ARIZONA.  1979.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      COMMON ETOL,ITMAX,NTIMES,FTRACE,STRACE,DELT,HDELT
      COMMON/FILES/INDATA,KLMIT,KOUT,LUTERM
C
C      *** PARAMETERS ***
C
C             TOTAL NUMBER OF EXTERNAL DEVICES WHICH CONTRIBUTE ENTHALPY
      JMAX=PARI(1) + .1
C
C             AREA OF COVER (M2)
      AC=PARI(2)
C
C             AREA OF SOIL (M2)
      AG=PARI(3)
C
C             VOLUME OF AIR INSIDE GREENHOUSE (M3)
      VAI=PARI(4)
C
C             FRACTION OF VENTILATION HEAT REMOVAL THAT IS LATENT
C             (0 TO LESS THAN 1, BUT MUST NOT EQUAL 1)
      FL=PARI(5)
C
C             CONTROL VARIABLE FOR NATURAL VENTILATION
C             (0 FOR SHUT AND 1 FOR OPEN)
      GAMN=XIN(8)
C             CONSTANT IN EQUATION FOR NATURAL VENTILATION (AIR CHANGES/H
      B2=(1.-GAMN)*PARI(6) + GAMN*PARI(8)
C
C             LINEAR COEF IN EQUATION FOR NATURAL VENTILATION
```

```
C             (AIR CHANGES/HR)/(M/S)
      B3=(1.-GAMN)*PARI(7) + GAMN*PARI(9)
C
C
C             MAXIMUM AIR CHANGES/HR WITH FAN VENTILATION
      ARMAX=PARI(10)
C
C             SATURATION EFFICIENCY OF EVAPORATIVE AIR COOLER (%)
      ETA=PARI(11)
C
C             REFLECTIVITY OF CROP AND/OR SOIL FOR SOLAR RADIATION
      RHOV=PARI(12)
C
C             CONTROL VARIABLE FOR SELECTING COVER PROPERTIES (0 TO 1)
      GAMC=XIN(6)
C
C             TRANSMISSIVITY OF COVER FOR SOLAR RADIATION
      TAUS=(1.-GAMC)*PARI(13) + GAMC*PARI(16)
C
C             CONSTANT IN EQUATION FOR U (W/M2 C)
      B0=(1.-GAMC)*PARI(14) + GAMC*PARI(17)
C
C             LINEAR COEFFICIENT IN EQUATION FOR U (W/M2 C)/(M/S)
      B1=(1.-GAMC)*PARI(15) + GAMC*PARI(18)
C
C
C       *** INPUTS ***
C
C             TOTAL DOWNCOMING SOLAR RADIATION (W/M2 OF GROUND AREA)
      ST=XIN(1)
C
C             OUTSIDE WIND SPEED (M/S)
      UAO = XIN(2)
C
C             BAROMETRIC PRESSURE (KPA)
      PAO=XIN(3)
C
C             OUTSIDE DRY BULB (C)
      TAO=XIN(4)
C
C             OUTSIDE WET BULB (C)
      TWBO=XIN(5)
C
C             CONTROL VARIABLE FOR POWERED VENTILATION
C             (0 FOR FANS OFF AND 1 FOR FANS ON)
      GAMP=XIN(7)
C
C             COMPUTE SUMS FOR AIR FLOWS (KG/S) FROM EXTERNAL
C             DEVICES.  TEMP IN DEG C.
      SUMTX=0.
```

```
      SUMMX=0.
      IF(JMAX.EQ.0) GOTO 2
      DO 1 J=1,JMAX
      JJ=9 + 2*(J-1)
      SUMMX=SUMMX + XIN(JJ+1)
      SUMTX=SUMTX + XIN(JJ+1)*XIN(JJ)
    1 CONTINUE
C      MULTIPLY BY HUMID AIR HEAT CAPACITY
      SUMMX=SUMMX*1020.
      SUMTX=SUMTX*1020.
    2 CONTINUE
C
C
C      COMPUTE SOLAR RADIATION ABSORBED BY GREENHOUSE
      SI=AG*ST*TAUS*(1.-RHOV)
C
C      COMPUTE COEFFICIEFNT OF HEAT TRANSMISSION
      U=B0 + B1*UAO
C
C      COMPUTE AIR DENSITY (KG/M3)
      DA=PAO/(.287*(TAO+273.16))
C
C      COMPUTE VENTILATION RATE IN AIR CHANGES/HR
C      NATURAL
      ARN=B2 + B3*UAO
      IF(GAMN.EQ. 1. .AND. ARN.LT.18.) ARN=18.
C      POWER VENTILATION RATE IN AIR CHANGES/HR
      ARP=GAMP*ARMAX
      AR=ARP
      IF(ARN.GT.ARP) AR=ARN
C      MULTIPLY BY GREENHOUSE VOLUME, AIR DENSITY, AND SPECIFIC HEAT
C      TO CONVERT TO W/C
      AR=(AR/3600.)*VAI*DA*1020.
C
C
C      TEST FOR LATENT FRACTION = 1.
      IF(FL.GT. .999) WRITE(KOUT,3)
    3 FORMAT(" *** WARNING  FL, FRACTION LATENT, HAS BEEN SET = .999")
      IF(FL.GT. .999) FL=.999
C
C      COMPUTE INSIDE GREENHOUSE TEMPERATURE
      TAI=SI + SUMTX + TAO*AC*U
      TAI=TAI + AR*(TAO - ETA*(TAO-TWBO))/(1.-FL)
      TAI=TAI/(AC*U + (AR/(1.-FL)) + SUMMX)
C
C
C      *** OUTPUTS ***
C
C             GREENHOUSE TEMPERATURE (C)
      OUTI(1)=TAI
```

```
C
C        SOLAR RADIATION ABSORBED BY GREENHOUSE (W)
       OUTI(2)=SI
C
C        TOTAL EXTERNAL HEAT SUPPLIED TO GREENHOUSE
       SUMX=0.
       IF(JMAX.EQ.0) GOTO 5
       DO 4 I=1,JMAX
       JJ=9 + 2*(I-1)
       SUMX=SUMX + XIN(JJ+1)*1020.*(XIN(JJ)-TAI)
   4   CONTINUE
   5   OUTI(3)=SUMX
C
C               TRANSMISSION OUT THROUGH COVER (INCLUDING THERMAL IR)  (W)
       OUTI(4)=AC*U*(TAI-TAO)
C
C               SENSIBLE HEAT REMOVED BY VENTILATION (W)
       OUTI(5)=AR*(TAI - TAO + ETA*(TAO-TWBO))
C
C               TOTAL SENSIBLE PLUS LATENT HEAT REMOVED BY VENTILATION(W)
       OUTI(6)=OUTI(5)/(1.-FL)
C
       RETURN
       END
```

```
C
      SUBROUTINE NSRAD
C
C             TYPE 17 NIGHT SKY RADIATOR
C
C             THIS SUBROUTINE SIMULATES A NIGHT SKY RADIATOR CONSISTING
C      OF A STREAM OF WATER COVERED BY A SELECTIVE SURFACE.  THE
C      RADIATOR HAS A COVER TRANSPARENT TO THERMAL RADIATION TO PROVIDE
C      AN INSULATING AIR LAYER.  WATER FLOWS IN ONE END AT
C      A GIVEN FLOW RATE AND THE COMPUTATION PROCEEDS SEGMENT-WISE
C      DOWN THE RADIATOR TO OBTAIN THE EXIT TEMPERATURE OF THE WATER.
C
C               THIS FIRST CASE IS THE NORMAL MODE 1.
C      AN ALTERNATIVE MODE 2 IS FOR THE CASE OF NO COVER AND
C      NO INSULATING AIR LAYER.  FOR THIS CASE SR NSRAD SETS THE
C      INSIDE CONVECTIVE HEAT TRANSFER COEFFICIENT EFFECTIVELY TO
C      INFINITY.  IT ALSO IGNORES PARAMETERS 8,9,10, AND 11 AND
C      INSTEAD SETS COVER TRANSMITTANCE TO ZERO AND USES
C      1 - SURFACE EMITTANCE FOR THE COVER REFLECTANCE.
C      ALSO THERE IS A MODE 3 WHERE THE COVER HUMIDITY
C      RATIO IS SET EQUAL TO SATURATION AT THE COVER TEMPERATURE.  WITH
C      NO INSULATING AIR LAYER AND A COVER TRANSMITTANCE = 0.0 AND
C      EMITTANCE =.96 FOR WATER, A POND CAN BE SIMULATED.
C      IN MODE 2 & 3 USER SHOULD SET SURFACE EMITTANCE  EQUAL TO
C      COVER VALUE.
C
C             PROGRAMMED BY B. A. KIMBALL, U. S. WATER CONSERVATION
C      LABORATORY, PHOENIX, ARIZONA.  1979.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      COMMON ETOL,ITMAX,NTIMES,FTRACE,STRACE,DELT,HDELT
      COMMON/FILES/INDATA,KLMIT,KOUT,LUTERM
      COMMON/NSR/TCOV,TSUR
      DIMENSION TW(11),TS(10),TC(10),R(10),H(10),E(10)
      REAL KDO,L
C
C      * FUNCTIONS *
C
C      SATURATION VAPOR PRESSURE (KPA FROM T IN C)
      SVP(T)=0.61078*EXP(17.2697*T/(T+237.3))
C
C      SATURATION HUMIDITY RATIO (KG/KG FROM P IN KPA AND T IN C)
      SHRO(P,T)=0.62198/((P/SVP(T))-1.)
C
C      LATENT HEAT OF VAPORIZATION (J/KG)
      HVAP(T)=2.501E6 -2381.*T
C
C
C      FRACTION OF BLACK BODY RADIATION IN 8-14 U BAND
      FW(T)=.34906 + 1.2495E-3*T - .91397E-5*T**2
```

```
C
C        *** PARAMETERS ***
C
C        LENGTH OF RADIATOR (M)
      XLEN=PARI(1)
C
C        WIDTH OF RADIATOR (M)
      WIDTH=PARI(2)
C
C
C        CONVECTIVE EXCHANGE COEFFICIENTS
      B0=PARI(3)
      B1=PARI(4)
C
C        CONSTANT AND EXPONENT FOR INSIDE TRANSFER COEF
      C0HI=PARI(5)
      C1HI=PARI(6)
C
C        CONSTANT IN EQN FOR WATER TRANSFER COEF
      CW=PARI(7)
C
C        TRANSMITTANCE AND REFLECTANCE OF DRY COVER FOR THERMAL RADIATION
C        INSIDE THE 8-14 U ATMOSPHERIC WINDOW AND OUTSIDE THE WINDOW.
      TCWD=PARI(8)
      TCOD=PARI(9)
      RCWD=PARI(10)
      RCOD=PARI(11)
C
C        EMITTANCE OF RADIATING SURFACE IN WINDOW AND OUTSIDE
      ESW=PARI(12)
      ESO=PARI(13)
C
C        MODE.  SET=1 FOR CASE OF TRANSPARENT COVER OVER INSULATING AIR
C                     LAYER.
C               SET=2 FOR CASE OF NO INSULATING AIR LAYER.  THEN PROGRAM
C                     WILL SET INSIDE CONVECTION TRANSPORT COEF EQUAL
C                     TO 500 W/M2/C
C               SET=3 FOR CASE OF WATER POND.  WCO, THE HUMIDITY RATIO
C                     AT COVER SURFACE WILL BE SET TO SATURATION VALUE
C                      AND TCO=TCW=0.0 AND ECW=ECO=ESW=ESO=.96 FOR WATER.
C                     AND INSIDE TRANSFER COEF = 500 W/M2/C
      MODE=PARI(14) + .01
C
C        PARAMETER TO GET SEGMENT BY SEBMENT SUMMARY PRINTED WHEN =1.
C        OTHERWISE SET = 0
      IPRNT=PARI(15)
C
C        NO. OF SEGMENTS
      NSEGS=PARI(16) + .01
C
```

```
C        EFFECTIVE TRANSMITTANCE-ABSORPTANCE PRODUCT FOR SOLAR RAD
        TAUALF=PARI(17)
C
C        *** INPUTS ***
C
C        ENTERING WATER TEMP (C)
        TW(1)=XIN(1)
C
C        WATER FLOW RATE (KG/S)
        F=XIN(2)
C
C        TOTAL LONG-WAVE SKY RADIATION (W/M2)
        RA=XIN(3)
C
C        8-14 U SKY RADIATION (W/M2)
        RAW=XIN(4)
C
C        SOLAR RADIATION IMPINGING ON RADIATOR (W/M2)
        SA=XIN(5)
C
C        OUTSIDE WINDSPEED (M/S)
        UAO=XIN(6)
C
C        BAROMETRIC PRESSURE
        P=XIN(7)
C
C        OUTSIDE DRY BULB TEMPERATURE (C)
        TAO=XIN(8)
C
C        OUTSIDE HUMIDITY RATIO (KG/KG)
        WAO=XIN(9)
C
C        *** INITIALIZATION ***
C
C        INITIALIZE STEPHAN-BOLTZMAN CONSTANT (W/M2 K4)
        SB=5.6697E-8
C
C        INITIALIZE WATER FLOW RATE CONSTANT (J/S C)
        FCON=2.*F*4190.
C
C        INITIALIZE  AREA OF EACH SEGMENT (M2)
        ASEG=(XLEN/FLOAT(NSEGS))*WIDTH
C
C
C        SKY RADIATION OUTSIDE WINDOW
        RAO=RA - RAW
C
C        ABSORBED SOLAR RADIATION
        S=TAUALF*SA
C
```

```
C       COMPUTE OUTSIDE AIR CONVECTIVE HEAT AND MASS TRANSFER COEFFICIENTS
C       (W/M2/C), (KG/M2/S)
      HO=BO+B1*UAO
      KDO=HO/(1005. + 1859.*WAO)
C
C       IF HAVE NO COVER (MODE = 2), SET THERMAL PROPERTIVES OF
C       PRETEND COVER TO SURFACE VALUES
      IF(MODE.NE.2) GOTO 2
      TCWD=0.
      TCOD=0.
      RCWD=1.-ESW
      RCOD=1.-ESO
C
C       INITIALIZE AVERAGE TEMPERATURE OF COVER AND SURFACE IN FIRST
C       SEGMENT TO BE VALUES LAST TIME THAT NSRAD WAS CALLED
    2 TSOLD=TSUR
      TCOLD=TCOV
      L=HVAP(TCOLD)
C
C       REFLECTANCE OF SURFACE
      RSW=1.-ESW
      RSO=1.-ESO
C
C   *** START LOOP FOR SEGMENTS ***
      DO 99 ISEG=1,NSEGS
C
C       IF ZERO FLOW RATE SET VALUES FOR THIS SEGMENT = VALUES FOR
C       PREVIOUS SEGMENT
      IF(ISEG.EQ.1) GOTO 31
      IF(F.GT. 1.E-4) GOTO 31
      TS(ISEG)=TS(ISEG-1)
      TC(ISEG)=TC(ISEG-1)
      TW(ISEG+1)=TW(ISEG)
      R(ISEG)=R(ISEG-1)
      H(ISEG)=H(ISEG-1)
      E(ISEG)=E(ISEG-1)
      GOTO 32
C
C       MAKE INITIAL GUESS FOR AVERAGE COVER AND SURFACE TEMPERATURE
C       IN MIDDLE OF SEGMENT TO BE THE SAME  TEMP AS IN THE LAST SEGMENT.
   31 IF(ISEG.GT.1) TSOLD=TS(ISEG-1)
      IF(ISEG.GT.1) TCOLD = TC(ISEG-1)
C
C       *** START ITERATION LOOP FOR COVER TEMPERATURE ***
      ITER=0
    9 ITER=ITER+1
C
      WCOLD=SHRO(P,TCOLD)
C       TEST IF HAVE DRY COVER OR DEW-WETTED COVER OR WATER POND
      IF(MODE.EQ.3) GOTO 6
```

```
      IF(WCOLD.LT.WAO) GOTO 6
C      HAVE DRY COVER
      SW=0.
      WCOLD=WAO
      TCW=TCWD
      TCO=TCOD
      RCW=RCWD
      RCO=RCOD
      GOTO 7
C      HAVE DEW-WETTED COVER OR WATER POND
    6 SW=WCOLD*(1.+WCOLD/0.62198)*4098.03/(TCOLD+237.3)**2
      TCW=0.
      TCO=0.
      RCW=0.04
      RCO=0.04
      L=HVAP(TCOLD)
    7 CONTINUE
C      EMITTANCE OF COVER
      ECW=1.-TCW-RCW
      ECO=1.-TCO-RCO
C      SUMS OF REFLECTED RAY FACTORS
      DNW=1.-RCW*RSW
      DNO=1.-RCO*RSO
      PAW=ECW*(1.+TCW*RSW/DNW)
      PAO=ECO*(1.+TCO*RSO/DNO)
      PSW=ECW/DNW
      PSO=ECO/DNO
      PCW= -2 + RSW*ECW/DNW
      PCO= -2 + RSO*ECO/DNO
      QAW=TCW*ESW/DNW
      QAO=TCO*ECO/DNO
      QSW= -1 + RCW*ESW/DNW
      QSO= -1 + RCO*ECO/DNO
      QCW=ESW/DNW
      QCO=ESO/DNO
C      OBTAIN ABSOLUTE TEMPS AND CUBES
      TCABS=TCOLD+273.16
      TSABS=TSOLD+273.16
      TC3=TCABS**3
      TS3=TSABS**3
C      FRACTIONS OF BB RADIATION IN AND OUT OF WINDOW
      FCW=FW(TCOLD)
      FCO=1.-FCW
      FSW=FW(TSOLD)
      FSO=1.-FSW
C      BB RADIATION AT OLD TEMPS AND SLOPES
      RBCOLD=SB*TC3*TCABS
      RBSOLD=SB*TS3*TSABS
      SC=4.*SB*TC3
      SS=4.*SB*TS3
```

```
C        SHORTENING VARIABLES
        PS=ESW*FSW*PSW + ESO*FSO*PSO
        PC=ECW*FCW*PCW + ECO*FCO*PCO
        QS=ESW*FSW*QSW + ESO*FSO*QSO
        QC=ECW*FCW*QCW + ECO*FCO*QCO
C        COMPUTE INSIDE HEAT TRANSFER COEF.  DIVIDE BY 2 SINCE HAVE 2
C        SURFACES.
        DT=ABS(TSOLD-TCOLD)
        IF(MODE.EQ.1) HI=(COHI*DT**C1HI)/2.
        IF(MODE.EQ.2 .OR. MODE.EQ.3) HI=500.
        IF(TCOLD.GT.TSOLD) HI=HI/2.
C        ESTIMATE WATER HEAT TRANSFER COEF
        HWCOEF=60.
        IF(ITER.EQ.1 .AND. TW(ISEG).GT.TSOLD)
     1         HWCOEF=CW*(TW(ISEG)-TSOLD)**.33
        IF(ITER.GT.1 .AND. TWAVE.GT.TSOLD) HWCOEF=CW*(TWAVE-TSOLD)**.33
        IF(HWCOEF.LT.60.) HWCOEF=60.
C        COMPUTE AVERAGE BULK WATER TEMP IN SEGMENT BASED ON OLD
C        ESTIMATE OF COVER TEMP
        TWAVE=FCON*TW(ISEG) + ASEG*HWCOEF*TSOLD
        TWAVE=TWAVE/(FCON + ASEG*HWCOEF)
C        COMPUTE LINEAR EQUATION COEFFICIENTS
        A1=PS*SS + HI
        B1=PC*SC - HO - L*KDO*SW - HI
        C1= -RAW*PAW -RAO*PAO - RBSOLD*PS + PS*SS*TSOLD
        C1=C1 - RBCOLD*PC + PC*SC*TCOLD
        C1=C1 - HO*TAO - L*KDO*(WAO-WCOLD + SW*TCOLD)
        A2=QS*SS - HI - HWCOEF
        B2=QC*SC + HI
        C2= -RAW*QAW - RAO*QAO - RBSOLD*QS + QS*SS*TSOLD
        C2=C2 - RBCOLD*QC + QC*SC*TCOLD
        C2=C2 - HWCOEF*TWAVE - S
C        SOLVE BY CRAMER'S RULE
        D=A1*B2 - A2*B1
        IF(ABS(D).LT. 1.E-20) GOTO 4
        TSNEW=(C1*B2 - C2*B1)/D
        TCNEW=(A1*C2 - A2*C1)/D
C        TEST FOR CONVERGENCE
C        USE .1 C FOR A COARSE TOLERANCE AND LET MAIN MEB PROGRAM
C        DO FINE TOLERANCE WITH ETOL
        IF(ABS(TSNEW-TSOLD).LT. 0.1 .AND. ABS(TCNEW-TCOLD).LT. 0.1)
     1      GOTO 14
        IF(ITER.GT.25) GOTO 4
C
C        CONVERGENCE NOT ATTAINED, RESET AND GO  BACK
        TCOLD=TCNEW
        TSOLD=TSNEW
        GOTO 9
C
C        CONVERGENCE NOT ATTAINED, ZERO DETERMINANT OR TOO MANY ITERATIONS
```

```
    4 WRITE(KOUT,13) ITER,ISEG,D,TWAVE,TCOLD,TSOLD,TCNEW,TSNEW
   13 FORMAT(" *** NSRAD NOT CONVERGED AFTER ",I3," ITERATIONS"/
     1       " ISEG = ",I3,"   D = ",E13.6,"   TWAVE = ",E13.6/
     2       " TCOLD = ",E13.6,"   TSOLD = ",E13.6/
     3       " TCNEW = ",E13.6,"   TSNEW = ",E13.6)
CC
C        CONVERGENCE ATTAINED.  COMPUTE TEMP OF THE WATER LEAVING SEGMENT.
   14 TC(ISEG)=TCNEW
      TS(ISEG)=TSNEW
      TW(ISEG+1)=TW(ISEG) - 2.*(TW(ISEG)-TWAVE)
C
C        COMPUTE THE NET THERMAL RADIATION,SENSIBLE, AND LATENT
C        HEAT ABOVE THE SEGMENT
      R(ISEG)=RAW*(1. - RCW - RSW*TCW**2/DNW)
      R(ISEG)=R(ISEG) + RAO*(1. - RCO - RSO*TCO**2/DNO)
      R(ISEG)=R(ISEG) + ESW*FSW*RBSOLD*(-TCW/DNW)
      R(ISEG)=R(ISEG) + ESO*FSO*RBSOLD*(-TCO/DNO)
      R(ISEG)=R(ISEG) + ECW*FCW*RBCOLD*(-1. - RSW*TCW/DNW)
      R(ISEG)=R(ISEG) + ECO*FCO*RBCOLD*(-1. - RSO*TCO/DNO)
      R(ISEG)=R(ISEG)*ASEG
      H(ISEG)=-ASEG*HO*(TC(ISEG) - TAO)
      E(ISEG)=-ASEG*L*KDO*(WCOLD - WAO)
C
   32 IF(IPRNT.NE.1) GOTO 99
C
C        PRINT OUT SEGMENT BY SEGMENT SUMMARY
      IF(ISEG.EQ.1) WRITE(KOUT,20)
C
C        TEST FOR ZERO FLOW RATE
      IF(ISEG.EQ.1) GOTO 33
      IF(F.LE. 1.E-4) GOTO 34
C
C        COMPUTE NET RADIATION BELOW COVER
   33 RNS=RAW*(TCW - TCW*RSW)/DNW
      RNS=RNS + RAO*(TCO - TCO*RSO)/DNO
      RNS=RNS + ESW*FSW*RBSOLD*(-1. + RCW)/DNW
      RNS=RNS + ESO*FSO*RBSOLD*(-1. + RCO)/DNO
      RNS=RNS + ECW*FCW*RBCOLD*(1. - RSW)/DNW
      RNS=RNS + ECO*FCO*RBCOLD*(1. - RSO)/DNO
      RNS=RNS*ASEG
C        COMPUTE SENSIBLE HEAT IN AIR UNDER COVER AND WATER
      AHEAT=ASEG*HI*(TCNEW - TSNEW)
      WHEAT=ASEG*HWCOEF*(TWAVE-TSNEW)
C
   20 FORMAT(1H0,4X,"---TEMPERATURES----  --ABOVE COVER-",
     1      "  --BELOW COVER-  TRANSFER COEFFICIENTS"/
     2      5X,"WATR SRFS COVR  AIR  RNET SENS  LAT  RNET ASEN",
     3      " WSEN    HO     HI     HW"/
     4      " ISEG --------(C)--------  ----(W/M2)----  ",
     5      " ----(W/M2)----  ------(W/M2/C)------")
```

```
   34   WRITE(KOUT,21)ISEG,TWAVE,TSNEW,TCNEW,TAO,R(ISEG),H(ISEG),E(ISEG),
     1      RNS,AHEAT,WHEAT,HO,HI,HWCOEF
    21 FORMAT(1X,I3,4F5.1,1X,3F5.0,1X,3F5.0,1X,3F7.2)
C
C        GO ON TO NEXT SEGMENT
   99   CONTINUE
C
C        *** OUTPUTS ***
C
C        EXIT WATER TEMPERATURE
        OUTI(1)=TW(NSEGS+1)
C
C        EXIT WATER FLOW RATE (= INLET FLOW RATE)(KG/S)
        OUTI(2)=XIN(2)
C        AVERAGE COVER AND SURFACE TEMPS (C)
        OUTI(3)=0.
        OUTI(4)=0.
        DO 17 I=1,NSEGS
        OUTI(3)=OUTI(3) + TC(I)
   17   OUTI(4)=OUTI(4) + TS(I)
        OUTI(3)=OUTI(3)/FLOAT(NSEGS)
        OUTI(4)=OUTI(4)/FLOAT(NSEGS)
C
C        TOTAL RATE OF ENERGY CHANG OF THE WATER (W)
        OUTI(5)=-F*4190.*(TW(1)-TW(NSEGS+1))
C
C        TOTAL RATE OF ENERGY CHANGE BY NET THERMAL RADIATION,SENSIBLE,
C        AND LATENT HEAT
        OUTI(6)=0.
        OUTI(7)=0.
        OUTI(8)=0.
        DO 16 ISEG=1,NSEGS
        OUTI(6)=OUTI(6)+ R(ISEG)
        OUTI(7)=OUTI(7) + H(ISEG)
        OUTI(8)=OUTI(8) + E(ISEG)
    16 CONTINUE
C
C        SAVE COVER AND SURFACE TEMPS FOR INITIAL VALUES NEXT TIME NSRAD CA
        TCOV=TC(1)
        TSUR=TS(1)
C
        RETURN
        END
```

```
C
      SUBROUTINE ROCK
C
C             TYPE 19 ROCK BED
C
C             THIS SUBROUTINE SIMULATES THE PERFORMANCE OF A ROCK BED
C       USED FOR THERMAL ENERGY STORAGE WITH AIR AS THE TRANSFER FLUID.  T
C       MODEL IS BASED ON THAT OF S.A. MUMMA AND W.C. MARVIN, 1976,
C       "A METHOD OF SIMULATING THE PERFORMANCE OF A PEBBLE BED THERMAL
C       ENERGY STORAGE AND RECOVERY SYSTEM," ASME-AICHE HEAT TRANSFER CONF
C       PARTICLE SIZE IS SMALL ENOUGH SO THAT TEMPERATURE GRADIENTS INSIDE
C       PARTICLES ARE INSIGNIFICANT, IE. THAT THE BIOT NUMBER, HR/K, IS LE
C       THAN 0.1
C
C             A SIGNIFICANT ENHANCEMENT TO MUMMA AND MARVIN IS THE ACCOUN
C       OF LATENT HEAT TRANSFER.  CONDENSATION OF MOISTURE CAN OCCUR ON TH
C       PARTICLES WHENEVER THE HUMIDITY RATIO OF THE  AIR EXCEEDS THE SATU
C       SIGNIFICANT ABSORPTION OF MOISTURE OCCURS , AND THAT IT DRAINS
C       AWAY.  THUS, CONDENSATION CAN OCCUR IN THE BED, BUT NOT EVAPORATIO
C
C             PROGRAMMED BY B.A. KIMBALL, .S. WATER CONSERVATION
C       LABORATORY, PHOENIX, ARIZONA. 1980.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      COMMON/FILES/INDATA,KLMIT,KOUT,LUTERM
      DIMENSION TA(11),WA(11),EA(11)
      REAL LEN, KAPPA, KV
C
C      SATURATION  VAPOR PRESSURE (KPA FROM C - TETENS' EQN)
      SVP(T)=0.61078*EXP(17.2694*T/(T+237.40))
C
C      SATURATION HUMIDITY RATIO (KG/KG)
      SHR(T,P)=0.62198/((P/SVP(T)) - 1.)
C
C      ENTHALPY (J/KG)
      EPY(T,W)=1005.*T + W*(2468.E3 + 1859.*T)
C
C      ***PARAMETERS***
C
C      NUMBER OF SEGMENTS
      NMAX=PARI(1)+ .1
      NMP1=NMAX + 1
      NMM1=NMAX - 1
C
C      LENGTH(M),AREA(M2),AND PERIMETER(M) OF ROCK BED
      LEN=PARI(2)
      DELL=LEN/FLOAT(NMAX)
      AREA=PARI(3)
      PER=PARI(4)
      AREAP=PER*DELL
```

```
C
C       EQUIVALENT DIAMETER OF INDIVIDUAL ROCKS(M)
      DR=PARI(5)
C
C       EFFECTIVE VOLUMETRIC HEAT CAPACITY OF ROCKS INCLUDING VOID
C       SPACE (J/(M3*C))
      CR=PARI(6)
C
C       LOSS COEFFICIENT (W/(M2*C)) AND AXIAL THERMAL CONDUCTIVITY(W/(MC))
      U=PARI(7)
      KAPPA=PARI(8)
      US=U*AREAP
      UE=U*(AREAP + AREA)
      IF(NMAX.EQ.1) UE=U*(AREAP + 2*AREA)
      KAPPA=KAPPA*AREA/DELL
C
C       DENOMINATOR FOR DTDT EQNS
      DENOM=AREA*DELL*CR
C
C       ***INPUTS***
C
C       TEMPERATURE(C),FLOW RATE(KG/S),AND HUMIDITY RATIO OF AIR  ENTERING
C       TOP AND BOTTOM
      TA(1)=XIN(1)
      FTOP=XIN(2)
      WA(1)=XIN(3)
      TA(NMP1)=XIN(4)
      FBOT=XIN(5)
      WA(NMP1)=XIN(6)
C
C       GET THE CONTROL VARIABLES THAT PROPORTION THE FLOW TO FRACTIONS
C       OF MAXIMUS AND DIVIDE TO SCALE UP THE FLOWS TO WHAT THEY ACTUALLY
C       WOULD BE FOR THE FRACTIONS OF TIME THE ROCK BED IS IN OPERATION.
C       USE THE ACTUAL MAX FLOWS TO COMPUTE THE VOLUMETRIC HEAT
C       TRANSFER COEFFICIENT (W/(M3*C)) FROM THE LOF AND HAWLEY EQUATION.
      GAMT=XIN(7)
      GAMB=XIN(8)
      GMAXT=0.
      IF(GAMT.LT. 1.E-6) GOTO 7
      GMAXT=FTOP/(AREA*GAMT)
    7 GMAXB=0.
      IF(GAMB.LT. 1.E-6) GOTO 8
      GMAXB=FBOT/(AREA*GAMB)
    8 GMAX=GMAXT
      IF(GMAXB.GT.GMAXT) GMAX=GMAXB
C       VOLUMETRIC HEAT TRANSFER COEFFICIENT
      HV=650.*(GMAX/DR)**.7
C
C       BAROMETRIC PRESSURE(KPA) AND TEMP(C) OF ENVIRONMENT AROUND
C       ROCK BED
```

```
      PRES=XIN(9)
      TENV=XIN(10)
C
C       TEST FOR FLOW DIRECTION
      IF(FBOT.EQ.0.) GOTO 100
      IF(FTOP.EQ.0.) GOTO 200
C
C       HAVE ILLEGAL CASE OF BOTH FLOWS ON AT SAME TIME.
C       BY AN ORDER OF MAGNITUDE
      RATIO=FTOP/FBOT
     IF(RATIO.GT. 0.1 .AND. RATIO.LT. 10.) WRITE(KOUT,10) FTOP,FBOT
 10  FORMAT(" ***WARNING - FLOW GOING UP AND DOWN IN ROCK BED.",
    A      " USING LARGER"/
    1      " FTOP= ",E13.5,"   FBOT= ",E13.5)
      IF(FBOT.GT.FTOP) GOTO 200
C
C       HAVE AIR FLOW FROM TOP TO BOTTOM OF BED
 100  F=FTOP
      FLDIR=+1.
      G=F/AREA
C       SPECIFIC HEAT OF AIR (J/KG)
      CA=1005. + WA(1)*1859.
C       VOLUMETRIC MASS TRANSFER COEF(KG/(S*M2))
      KV=HV/CA
C       EXPOENTIAL DECAY FACTOR
      EXDF=0.
      IF(G.LT. 1.E-6) GOTO 101
      KV=KV*DELL/G
      IF(KV .LT. 50.) EXDF=EXP(-KV)
C       AIR ENTHALPY ENTERING TOP
 101  EA(1)=EPY(TA(1),WA(1))
C
C       LOOP TO COMPUTE AIR ENTHALPY, TEMP, HUM RATIO LEAVING EACH SEGMENT
      DO 110 N=1,NMAX
C
C       COMPUTE SAT HUM RATIO AT ROCK TEMP FOR SEGMENT
      WR=SHR(TI(N),PRES)
      IF(WR.GE.WA(N)) WR=WA(N)
C       AIR ENTHALPY AT ROCK INTERFACE
      ER=EPY(TI(N),WR)
C
      EA(N+1)=(EA(N)-ER)*EXDF + ER
      TA(N+1)=TI(N) + (TA(N)-TI(N))*EXDF
      WA(N+1)=(EA(N+1)-1005.*TA(N+1))/(2468.E3 + 1859.*TA(N+1))
 110  CONTINUE
      GOTO 290
C
C
C       HAVE AIR FLOW FROM BOTTOM TO TOP OF BED
 200  F=FBOT
```

```
      FLDIR=-1.
      G=F/AREA
C      SPECIFIC HEAT OF AIR (J/KG)
      CA=1005. + WA(NMP1)*1859.
C      VOLUMETRIC MASS TRANSFER COEF (KG/(S*M2))
      KV=HV/CA
C      EXPOENTIAL DECAY FACTOR
      EXDF=0.
      IF(G.LT. 1.E-6) GOTO 201
      KV=KV*DELL/G
      IF(KV.LT. 50.) EXDF=EXP(-KV)
C      AIR ENTHALPY ENTERING BOTTOM
  201 EA(NMP1)=EPY(TA(NMP1),WA(NMP1))
C
C      LOOP TO COMPUTE AIR ENTHALPY, TEMP,HUM RATIO LEAVING EACH SEGMENT
      DO 210 N=1,NMAX
      NM=NMP1-N
C
C      COMPUTE SAT HUM RATIO AT ROCK TEMP FOR SEGMENT
      WR=SHR(TI(NM),PRES)
      IF(WR.GE.WA(NM+1)) WR=WA(NM+1)
C      AIR ENTHALPY AT  ROCK INTERFACE
      ER=EPY(TI(NM),WR)
C
      EA(NM)=(EA(NM+1)-ER)*EXDF + ER
      TA(NM)=TI(NM) + (TA(NM+1)-TI(NM))*EXDF
      WA(NM)=(EA(NM) - 1005.*TA(NM))/(2468.E3 + 1859.*TA(NM))
  210 CONTINUE
C
C
C      COMPUTE RATE OF TEMP CHANGE OF ROCKS
C
C      FOR TOP SEGMENT
  290 TQENV=UE*(TI(1)-TENV)
      DTDTI(1)=(FLDIR*F*(EA(1)-EA(2)) - TQENV)/DENOM
      IF(NMAX.EQ.1) GOTO 320
      DTDTI(1)=DTDTI(1) - KAPPA*(TI(1)-TI(2))/DENOM
C
C      MIDDLE SEGMENTS
      IF(NMAX.EQ.2) GOTO 310
      DO 300 N=2,NMM1
      QENV=US*(TI(N)-TENV)
      TQENV=TQENV + QENV
      DTDTI(N)=FLDIR*F*(EA(N)-EA(N+1)) - QENV
      DTDTI(N)=DTDTI(N) + KAPPA*(TI(N+1) - 2.*TI(N) + TI(N-1))
      DTDTI(N)=DTDTI(N)/DENOM
  300 CONTINUE
C
C      FOR BOTTOM SEGMENT
  310 QENV=UE*(TI(NMAX) - TENV)
```

```
      TQENV=TQENV + QENV
      DTDTI(NMAX)=FLDIR*F*(EA(NMAX)-EA(NMP1)) - QENV
      DTDTI(NMAX)=DTDTI(NMAX) + KAPPA*(TI(NMM1)-TI(NMAX))
      DTDTI(NMAX)=DTDTI(NMAX)/DENOM
C
C      ***OUTPUTS***
C
C      TEMP(C), FLOW RATE(KG/S), HUM RATIO OF AIR LEAVING BOTTOM
  320 OUTI(1)=TA(NMP1)
      OUTI(2)=FTOP
      OUTI(3)=WA(NMP1)
C
C      TEMP, FLOW RATE, HUM RATIO OF AIR LEAVING TOP
      OUTI(4)=TA(1)
      OUTI(5)=FBOT
      OUTI(6)=WA(1)
C
C      RATE OF TOTAL ENERGY ADDITION TO BED FROM STREAM ENTERING TOP (W)
      OUTI(7)=FTOP*(EA(1)-EA(NMP1))
C
C      RATE OF WATER CONDENSATION FROM STREAM ENTERING TOP (KG/S)
      OUTI(8)=FTOP*(WA(1)-WA(NMP1))
C
C      RATES OF ENERGY ADDITION AND WATER CONDENSATION FROM BOTTOM STREAM
      OUTI(9)=FBOT*(EA(NMP1)-EA(1))
      OUTI(10)=FBOT*(WA(NMP1)-WA(1))
C
C      RATE OF ENERGY LOSS TO THE ENVIRONMENT (W)
      OUTI(11)=TQENV
C
C      ROCK BED TEMPERATURES (C) BY SEGMENT
      DO 330 N=1,NMAX
  330 OUTI(N+11)=TI(N)
C
      RETURN
      END
```

```
COVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOV
      PROGRAM MEBV3(5)
      DIMENSION IPAR(5)
      CALL RMPAR(IPAR)
      INSTN=IPAR(1)
      GOTO INSTN
      END
```

```
COVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOVOV
C
      SUBROUTINE CGH
C
C      TYPE 14       COMPLICATED GREENHOUSE
C
C             THIS SUBROUTINE DOES A DETAILED SIMUALTION OF THE ENERGY
C      BALANCES OCCURING AT THE OUTER COVER SURFACE, INNER COVER
C      SURFACE, VEGETATION, SOIL SURFACE, CURTAIN HEAT EXCHANGER, SOIL
C      STORAGE LAYER, AND AIR, AND A MASS  BALANCE ON THE AIR.
C      ALL SOLAR AND THERMAL RADIATION AND SENSIBLE AND LATENT
C      AND SOIL CONDUCTION HEAT FLUXES ARE COMPUTED INDIVIDUALLY.
C
C             PROGRAMMED BY B. A. KIMBALL, U. S. WATER CONSERVATION
C      LABORATORY, PHOENIX, ARIZONA.  1979.
C
      COMMON TIME,XIN(40),OUTI(80),TI(10),DTDTI(10),PARI(99)
      COMMON ETOL,ITMAX,NTIMES,FTRACE,STRACE,DELT,HDELT
      COMMON/FILES/INDATA,KLMIT,KOUT,LUTERM
      COMMON/CGHMN/GHOLD(8),MMAX,BR,GS(3),GSOLD(3),GSUM(4),TD,
     1   BRF(4,24),TGOOLD(26),TGSOLD(26),GHTIME
      DIMENSION C(10),A(8,9),GH(8),B(13),S(5,9),TX(5),WX(5)
      DIMENSION GAM(7),GM1(7),AF(5,5),EP(14),GEOM(18),RHO(5)
      DIMENSION V(5,5),EPW(5)
      REAL LO,LI,NRV,K(10),UC,KDF,KDN,MX(4),MXC,MXG,MXE
C
C
C      ***FUNCTIONS ***
C
C      SATURATION VAPOR PRESSURE (TETENS) (KPA FROM T IN C)
      SVP(T)=0.61078*EXP(17.2694*T/(T+237.3))
C
C      SATURATION HUMIDITY RATIO (KG/KG FROM P IN KPA AND T IN C)
      SHRO(P,T)=.62198/((P/SVP(T))-1.)
C
C      HUMIDITY RATIO (KG/KG FROM P AND VP IN KPA)
      HRO(P,VP)=.62198*VP/(P-VP)
C
C      SLOPE OF HUMIDITY RATIO VS TEMPERATURE CURVE
      SW(W,T)=W*(1. + W/0.62198)*4098.03/(T+237.3)**2
C
C      HUMID SPECIFIC HEAT (J/KG C)
      HSH(W)= 1005. + 1859*W
C
C      LATENT HEAT OF VAPORIZATION (J/KG)
      HVAP(T)=2.501E6 - 2381.*T
C
C      MASS TRANSFER COEFFICIENT FROM HEAT TRANSFER COEFFICIENT (KG/S M2)
      FKD(H,W)=H/(1005. + 1859.*W)
C      CONTROL VARIABLE FOR: 1-COVER FLUID,2-COVER PROPERTIES
```

```
C        3-POWERED AIR CIRCULATION,4-NATRUAL VENTILATION,
C        5-CURTAIN HEAT EXCHANGER HEIGHT
         DO 42 I=1,7
         GAM(I)=XIN(I+8)
    42  GM1(I)=1.-GAM(I)
C
C
C        *** PARAMETERS ***
C
C               TOTAL NUMBER OF EXTERNAL DEVICES  WITH
C               SENSIBLE AND LATENT HEAT FLUXES)
        JMAX=PARI(1) + .1
C
C               AREA OF COVER (M2)
        GEOM(1)=PARI(2)
C
C        AREA OF SOIL (M2)
        GEOM(3)=PARI(3)
C
C               VOLUME OF AIR IN GREENHOUSE (M3)
        GEOM(5)=PARI(4)
C
C               LENGTH OF ROW OF VEGETATION = LENGTH OF GREENHOUSE (M)
        GEOM(6)=PARI(5)
        IF(GEOM(6).LE. 0.) GEOM(6)= 0.1
C
C               ROW SPACING (MUST NOT = 0. !) (M)
        GEOM(7)=PARI(6)
        IF(GEOM(7).LE.0.) GEOM(7)= 1.0
C
C        NUMBER OF VEGETATION ROWS PER CURTAIN HEAT EXCHANGER
        GEOM(8)=PARI(7)
        NE=GEOM(8)+.01
C
C        HEIGHT OF CURTAIN HEAT EXCHANGER(M)
        GEOM(10) = PARI(8)*GAM(6)
        IF(GEOM(10) .LT. .001) GEOM(10)=.001
C
C        REFLECTANCE OF VEGETATION FOR SOLAR
        RHOV= PARI(9)
C
C        REFLECTANCE OF SOIL FOR SOLAR
        RHOG=PARI(10)
C
C        EMITTANCE OF DRY VEGETATION FOR THERMAL RAD
        EP(10) = PARI(11)
C
C        EMITTANCE OF DRY SOIL FOR THERMAL
        EP(12)= PARI(12)
C
```

```
C        EMITTANCE OF DRY CURTAIN HEAT EXCHANGER
        EP(14)=PARI(13)
C
C        HEAT CAPACITY OF COVER FLUID(J/KG/C)
        CXC=PARI(14)
C
C        HEAT CAPACITY OF SOIL FLUID (J/KG/C)
        CXG =PARI(15)
C
C        HEAT CAPACITY OF CURTAIN HEAT EXCHANGER FLUID
        CXE = PARI(16)
C
C               CONSTANT IN EQUATION FOR OUTSIDE TRANSFER COEFFICIENT (W/M2
        B(1)=PARI(17)
C
C               LINEAR COEFFICIENT IN EQUATION FOR OUTSIDE TRANSFER
C               COEFFICIENT (W/M2 C)/(M/S)
        B(2)=PARI(18)
C
C               CONSTANT IN EQUATION FOR INSIDE TRANSFER COEFFICIENT
C               (W/M2 C)/(C)**1/B(4)
        B(3)=PARI(19)
C
C               EXPONENT IN EQUATION FOR INSIDE TRANSFER COEFFICIENT
        B(4)=PARI(20)
C
C        CONSTANTS IN EQUATION FOR NATURAL VENTILATION THROUGH VENTILATORS
        B(5)=GAM(5)*PARI(21)
        B(6)=GAM(5)*PARI(22)
        B(7)=GAM(5)*PARI(23)
C
C
C        STOMATAL RESISTANCE
        B(8)=PARI(24)
        B(9)=PARI(25)
        B(10)=PARI(26)
C
C        SOIL SURFACE RESISTANCE (M2*S/KG)
        RSOIL=PARI(27)
C
C        INSIDE HEAT TRANSFER COEF WHEN POWER
C        CIRCULATION FAN IS ON (W/(M2*C))
        HPOWR = PARI(28)*GAM(4)
C
C        INFRARED HEATER CAPACITY(W) AND RADIENT FRACTION
        XR=PARI(29)*GAM(7)
        FR=PARI(30)
C
C
C        TRANSMITTANCE OF OUTER AND INNER COVER FOR SOLAR
```

```
      TAUSO=GM1(2)*PARI(31) + GAM(2)*PARI(32)
      TAUSI=GM1(1)*GM1(3)*PARI(33) + GM1(1)*GAM(3)*PARI(34)
     1 +GAM(1)*GM1(3)*PARI(35)+GAM(1)*GAM(3)*PARI(36)
C
C
C
C       ABSORPTANCE OF OUTER AND INNER COVER FOR SOLAR
      ALSO = GM1(2)*PARI(37) + GAM(2)*PARI(38)
      ALSI = GM1(1)*GM1(3)*PARI(39) + GM1(1)*GAM(3)*PARI(40)
     1 +GAM(1)*GM1(3)*PARI(41) + GAM(1)*GAM(3)*PARI(42)
C
C       THERMAL CONDUCTANCE OF COVER (W/(M2C))
      UC=GM1(1)*GM1(3)*PARI(43)+GM1(1)*GAM(3)*PARI(44)
     1 +GAM(1)*GM1(3)*PARI(45)+GAM(1)*GAM(3)*PARI(46)
      UC=UC*GEOM(1)
C
C
C       TRANSMITTANCE OF DRY OUTER AND INNER COVER FOR THERMAL RADIATION
      TDO= GM1(2)*PARI(47) +GAM(2)*PARI(48)
      TDI = GM1(1)*GM1(3)*PARI(49) + GM1(1)*GAM(3)*PARI(50)
     1 +GAM(1)*GM1(3)*PARI(51) + GAM(1)*GAM(3)*PARI(52)
C
C       EMMITTANCE OF DRY OUTER AND INNER SIDES OF OUTER COVER FOR THERMAL
      EP(2)=GM1(2)*PARI(53)+GAM(2)*PARI(54)
      EP(4) =GM1(2)*PARI(55) +GAM(2)*PARI(56)
C
C     EMITTANCE OF DRY OUTER AND INNER SIDES OF INNER COVER FOR THERMAL
C     RADIATION
      EP(6)=GM1(1)*GM1(3)*PARI(57) + GM1(1)*GAM(3)*PARI(58)
     1 +GAM(1)*GM1(3)*PARI(59) + GAM(1)*GAM(3)*PARI(60)
C
      EP(8)=GM1(1)*GM1(3)*PARI(61)+GM1(1)*GAM(3)*PARI(62)
     1 +GAM(1)*GM1(3)*PARI(63)+GAM(1)*GAM(3)*PARI(64)
C       COEFFICIENTS FOR INFILTRATION
      B(11)=GM1(3)*GM1(4)*PARI(65)+GM1(3)*GAM(4)*PARI(66)
     1 +GAM(3)*GM1(4)*PARI(67)+GAM(3)*GAM(4)*PARI(68)
      B(12)=GM1(3)*GM1(4)*PARI(69)+GM1(3)*GAM(4)*PARI(70)
     1 +GAM(3)*GM1(4)*PARI(71)+GAM(3)*GAM(4)*PARI(72)
      B(13)=GM1(3)*GM1(4)*PARI(73)+GM1(3)*GAM(4)*PARI(74)
     1 +GAM(3)*GM1(4)*PARI(75)+GAM(3)*GAM(4)*PARI(76)
C
C
C       *** INPUTS ***
C
C              TOTAL DOWNCOMING SOLAR RADIATION (W/M2)
      ST=XIN(1)
C
C              THERMAL RADIATION FROM SKY AND OUTSIDE GROUND (W)
      RAO=XIN(2)*(GEOM(3) + (GEOM(1)-GEOM(3))/2.)
      RGO=((GEOM(1)-GEOM(3))/2.)*5.6697E-8*(XIN(5)+273.16)**4
```

```
C
C               OUTSIDE WIND SPEED (M/S)
      UAO=XIN(3)
C
C               OUTSIDE BAROMETRIC PRESSURE(KPA)
      PAO=XIN(4)
C
C               OUTSIDE AIR TEMP (C)
      TAO=XIN(5)
C
C               OUTSIDE HUMIDITY RATIO (KG/KG)
      WAO=XIN(6)
C
C               HEIGHT OF ROW OF VEGETATION (M)  (SET=0. FOR NO. VEG)
      GEOM(9)=XIN(7)
      IF(GEOM(9).LE. 0.) GEOM(9)= 0.001
C
C               WIDTH OF ROW OF VEGETATION (M)  (0 TO GEOM(7))
      GEOM(11)=XIN(8)
      IF(GEOM(11) .LE. 0.) GEOM(11)=0.001
C
C
C      TEMPERATURE(C)AND MASS FLOW RATES(KG/S) OF
C      FLUIDS FROM EXTERNAL DEVICES TO COVER, SOIL, AND
C      CURTAIN HEAT EXCHANGER
      TXC=XIN(16)
      MXC=XIN(17)*CXC*2.
      TXG=XIN(18)
      MXG=XIN(19)*CXG*2.
      TXE=XIN(20)
      MXE = XIN(21)*CXE*2.
C
C               GET TEMP, FLOW RATE, AND HUMIDITY FROM EXTERNAL DEVICES
C      GOING TO GREENHOUSE AIR
      SUMMX =0.
      SUMEX=0.
      IF(JMAX.EQ.0.) GOTO 4
      DO 3 J=1,JMAX
      JJ=22 + (J-1)*3
      TX(J)=XIN(JJ)
      MX(J)=XIN(JJ+1)
      WX(J)=XIN(JJ+2)
      SUMMX=SUMMX + MX(J)
      SUMEX=SUMEX + WX(J)*MX(J)
    3 CONTINUE
    4 CONTINUE
C
C               GEOM             EP       EPW     RHO
C        1       AC               EPCOO EPCOI RHCOI
C        2       AV               EPCOOD EPCII   RHOCEFF
```

```
C        3       AG                EPCOI EPV     RHOV
C        4       AE                EPCOID EPG     RHOG
C        5       VAI              EPCIO   EPE     RHOE
C        6       L                EPCIOD
C        7       S                EPCII
C        8       NE                EPCIID
C        9       Y                EPV
C        10     X                  EPVD
C        11     W                  EPG
C        12     AVS                EPGD
C        13     W/2                EPE
C        14     NES                EPED
C        15     X-Y
C        16     Y+W
C        17     NS
C        18     S-W
C        CODE FOR GH( ), GHOLD( ), AND S( , )
C        GH( ) GHOLD( )
C  1    TCO      TCOOLD
C  2    TCI      TCIOLD
C  3    TV        TVOLD
C  4    TG        TGOLD
C  5    TE       TEOLD
C  6    TAI      TAIOLD
C  7    WAI      WAIOLD
C
C  I    S(I,1) S(I,2) S(I,3) S(I,4) S(I,5) S(I,6) S(I,7) S(I,8)  S(I,9)
C  1    HO        KDO     RCOOLD SRCO     YRCO    WCOOLD SWCO   YWCO     YCON
C  2    HICI      KDCI   RCIOLD SRCI   YRCI     WCIOLD SWCI     YWCI   YCIN
C  3    HIV      KDV      RVOLD    SRV      YRV     WVOLD   SWV      YWV      YYN
C  4    HIG      KDG      RGOLD    SRG      YRG     WGOLD   SWG      YWG      YGN
C  5    HIE      KDE      REOLD    SRE      YRE     WEOLD   SWE      YWE      YEN
C        *** NON-ITERATIVE VARIABLES ***
C
        PI=3.14159
C
        TPI=2.*PI
C        STEPHAN-BOLTZMAN (W/M2 K4)
        SB=5.6697E-8
C
C        COMPUTE NO. ROWS VEGETATION AND VEGETATION AREA
         IF(GEOM(7) .EQ. 0. .OR. GEOM(6) .EQ. 0.) WRITE(KOUT,41)
   41   FORMAT(" ROW SPACING OR ROW LENGTH EQUALS ZERO")
        NRV=0.
        IF(GEOM(7) .NE. 0. .AND. GEOM(6).NE. 0.) NRV=GEOM(3)/
     1       (GEOM(7)*GEOM(6))
        GEOM(2)=2.*NRV*GEOM(6)*(GEOM(11) + GEOM(9))
C        VEGETATION AREA FOR ABSORPTION OF SLOAR RADIATION
        GEOM(12)=NRV*GEOM(6)*(GEOM(11) + GEOM(9))/2.
        IF(GEOM(12) .GT. GEOM(3)) GEOM(12)=GEOM(3)
```

```
C       AVERAGE REFLECTANCE OF VEGETATION AND SOIL
        RHOVG=(RHOV*GEOM(12) + (GEOM(3)-GEOM(12))*RHOG)/GEOM(3)
C
C       TOTAL CURTAIN HEAT EXCHANGER AREA
      GEOM(4)=2.*NRV*GEOM(6)*GEOM(10)/GEOM(8)
      GEOM(13)=GEOM(11)/2.
      GEOM(14)=GEOM(8)*GEOM(7)
      GEOM(15)=GEOM(10)-GEOM(9)
      GEOM(16)=GEOM(9)+GEOM(11)
      GEOM(18)=GEOM(7)-GEOM(11)
C       WRITE(KOUT)(GEOM(I),I=1,18)
C
C
C       ANGLE FACTORS FOR THERMAL RADIATION
C       COVER TO COVER
      AF(2,2)=1.-(GEOM(3)/GEOM(1))
C
C       EXCHANGER TO COVER
      AF(5,2)=0.
      IF(GEOM(15) .LE.0.) GO TO 43
      AF(5,2)=.5
      IF(GEOM(10).LE.1.E-3)GO TO 43
      BETA=2.*ATAN(GEOM(15)/(2.*GEOM(14)))
      AF(5,2)=(GEOM(15)/GEOM(10))*(PI-BETA)/TPI
C       EXCHANGER TO SOIL
   43 AF(5,4)=0
      IF(GEOM(15).LE.0.)GO TO 46
      AF(5,4)=.5
      IF(GEOM(10).LE.1.E-3)GO TO 46
      AF(5,4)=AF(5,2)
      IF(GEOM(9).LE.1.E-3) GOTO 46
      SBETA=0.
      N=0
   44 N=N+1
      BETA=ATAN((FLOAT(N)*GEOM(7)-GEOM(13))/(GEOM(9)+(GEOM(15)/2.)))
      BETA=BETA-ATAN((FLOAT(N)*GEOM(7)-GEOM(13)-GEOM(18))/
     1       (GEOM(15)/2.))
      IF (BETA .LE. 0.)GO TO 45
      SBETA=SBETA+BETA
      IF(N .GE. NE) GO TO 45
      GO TO 44
   45 AF(5,4)=(GEOM(15)/GEOM(10))*(SBETA/PI)
C       EXCHANGER TO VEGETATION
   46 IF(GEOM(15).LE.0.)AF(5,3)=1.
      IF(GEOM(15).GT.0.)AF(5,3)=(GEOM(9)/GEOM(10))+AF(5,2)-AF(5,4)
C       EXCHANGER TO EXCHANGER
      AF(5,5)=1.-AF(5,2)-AF(5,3)-AF(5,4)
C
C       SOIL TO COVER AND SOIL TO EXCHANGER
      AF(4,2)=0.
```

```
      AF(4,5)=0.
C      CHECK CLOSED CANOPY
      IF(GEOM(18).LT.1.E-6)GO TO 48
C      CHECK EXCHANGER SHORTER THAN VEGATATION, VEGETATION ZERO
      AF(4,2)=1.
      IF(GEOM(10).LE.GEOM(9) .AND. GEOM(9).LE.1.E-3)GO TO 48
      IF(GEOM(10).LE. 1.E-3 .AND. GEOM(9).LE. 1.E-3) GOTO 48
C      SHORT EXCHANGER, TALL VEGETATION
      IF(GEOM(10).GT.GEOM(9))GO TO 55
      BETA=2.*ATAN(GEOM(18)/(2.*GEOM(9)))
      AF(4,2)=(GEOM(18)/GEOM(7))*BETA/PI
      GOTO 48
C      TALL EXCHANGER, SHORT VETETATION
   55 IF(GEOM(9).GT.1.E-3)GO TO 56
      AF(4,2)=2.*ATAN(GEOM(14)/(2.*GEOM(10)))/PI
      AF(4,5)=1.-AF(4,2)
      GO TO 48
C      TALL EXCHANGER, TALL VEGETATION
   56 BETAC=2.*ATAN(GEOM(18)/(2.*GEOM(9)))
      BETAM=ATAN(2.*GEOM(9)/GEOM(18))
      SBETA=0.
      DO 47 N=1,NE
      BETA=ATAN(GEOM(10)/(FLOAT(N)*GEOM(7)-(GEOM(7)/2.)))-BETAM
      IF(BETA.GT.0.) SBETA=SBETA+BETA
   47 CONTINUE
      SBETA=SBETA*2./GEOM(8)
      AF(4,2)=(GEOM(18)/GEOM(7))*(BETAC-SBETA)/PI
      AF(4,5)=(GEOM(18)/GEOM(7))*SBETA/PI
C
C      SOIL TO VEGETATION
   48 AF(4,3)=1.-AF(4,2)-AF(4,5)
C      SOIL TO SOIL
      AF(4,4)=0.
C
C      VEGETATION TO SOIL
      AF(3,4)=.5
      IF(GEOM(16).LE.1.E-3) GO TO 68
      BETAC = PI/2.
      IF(GEOM(9).GT.1.E-3) BETAC=ATAN(2.*GEOM(18)/GEOM(9))
      AF(3,4)=(GEOM(11)+2.*GEOM(9)*(BETAC/PI))/(2.*(GEOM(16)))
C
C      VEGETATION TO COVER
   68 AF(3,2)=.5
C      VERY SHORT VEGETATION, PICK .5 AND MOVE ON
      IF(GEOM(16).LE.1.E-3) GO TO 58
C      TALL VEGETATION, SHORT EXCHANGER
      IF(GEOM(10).GT.GEOM(9)) GO TO 57
      BETA=0.
      IF(GEOM(18).LT.1.E-3) GO TO 60
      BETA=ATAN(GEOM(18)/(GEOM(9)/2.))
```

```
   60   AF(3,2)=(GEOM(11)+2.*GEOM(9)*(BETA/PI))/(2.*(GEOM(16)))
        GO TO 58
C        TALL VEGETATION, TALL EXCHANGER
   57   SBETA=0.
        DO 49 N=1,NE
        GEOM(17)=FLOAT(N)*GEOM(7)
        BETA=ATAN((GEOM(17)-(GEOM(11)/2.))/(GEOM(10)-(GEOM(9)/2.)))
        IF(BETA.GT.BETAC) BETA =BETAC
        SBETA=SBETA+BETA
        BETA=ATAN((GEOM(14)-GEOM(17)+GEOM(18)+(GEOM(11)/2.))/
     1       (GEOM(10)-(GEOM(9)/2.)))
        IF(BETA.GT.BETAC) BETA =BETAC
        SBETA=SBETA+BETA
   49   CONTINUE
        SBETA=SBETA*GEOM(9)
        DO 50 N=1,NE
        BETA=PI/2.
        IF(GEOM(10).GT.GEOM(9))BETA=ATAN(GEOM(15)/
     1     (FLOAT(N-1)*GEOM(7)+(GEOM(11)/4.)))
        SBETA=SBETA+BETA*GEOM(11)
        IF(GEOM(10).GT.GEOM(9))BETA=ATAN(GEOM(15)/(GEOM(14)
     1    -FLOAT(N-1)*GEOM(7)-(GEOM(11)/4.)))
        SBETA=SBETA+BETA*GEOM(11)
   50   CONTINUE
        AF(3,2)=SBETA/(TPI*GEOM(8)*(GEOM(16)))
C
C        VEGETATION TO VEGETATION
   58   AF(3,3)=0
        IF(GEOM(16).LT.1.E-3) GO TO 51
        BETAC=PI
        IF(GEOM(18).GT.1.E-6) BETAC=2.*ATAN((GEOM(9)/2.)/GEOM(18))
        AF(3,3)=(GEOM(8)-1.)*GEOM(9)*BETAC+.5*GEOM(9)*BETAC
        IF(GEOM(10).LT.GEOM(9))AF(3,3)=AF(3,3)+.5*(GEOM(9)-GEOM(10))
     1                 *BETAC
        AF(3,3)=AF(3,3)/(PI*GEOM(8)*(GEOM(16)))
C
C        VEGETATION TO HEAT EXCHANGER
   51   AF(3,5)=1.-AF(3,4)-AF(3,2)-AF(3,3)
C
C        COVER TO EXCHANGER
        AF(2,5)=0
        IF(GEOM(10).LE.GEOM(9).OR.GEOM(10) .LE. .001) GO TO 54
        BETA=ATAN((2.*GEOM(15))/GEOM(14))
        AF(2,5)=(GEOM(3)/GEOM(1))*2.*BETA/PI
C        COVER TO SOIL
   54   AF(2,4)=AF(4,2)*(GEOM(3)/GEOM(1))
C        COVER TO VEGETATION
        AF(2,3)=1.-AF(2,4)-AF(2,5)-AF(2,2)
C
C        COMPUTE SOLAR RADIATION ABSORBED BY COVER, VEGETAION, AND SOIL
```

```
          SCO=ST*GEOM(3)*ALSO*(1.+TAUSO*TAUSI*RHOVG*TAUSI)
         SCI=ST*GEOM(3)*TAUSO*ALSI*(1.+TAUSI*RHOVG)
         SV=ST*GEOM(12)*TAUSO*TAUSI*(1.-RHOV)
         SG=ST*(GEOM(3)-GEOM(12))*TAUSO*TAUSI*(1.-RHOG)
C
C         COMPUTE AIR DENSITY
         DA=PAO/(.287*(TAO+273.16))
C
C         COMPUTE OUTSIDE CONVECTIVE HEAT (W/M2 C) AND MASS (KG/S M2)
C         TRANSFER COEFFICIENTS
         S(1,1)=(B(1) + B(2)*UAO)*GEOM(1)
         LO=HVAP(TAO)
         S(1,2)=LO*FKD(S(1,1),WAO)
C
C         COMPUTE LEAF STOMATAL RESISTANCE (M2 S/KG)
         RS=B(8) + B(9)/(B(10) + ST*TAUSO*TAUSI)
C
C
C         COMPUTE OLD HUMIDITY RATIOS AND SLOPES.  CHANGE EMITTANCES AND
C         TRANSMITTANCES IF NECESSARY TO ACCOUNT FOR CONDENSATE FILMS.  REME
C         THAT IF THE DRY TRANSMITTANCE OF A COVER = 1.0, THEN ASSUME
C        HAVE NO COVER.   FIRST, INITIALIZE TO DRY VALUES.
         TRO=TDO
         TRI=TDI
         DO 70 I=1,13,2
      70 EP(I)=EP(I+1)
C         GET SATURATION HUMIDITY RATIOS FOR THE COVERS
         S(1,6)=SHRO(PAO,GHOLD(1))
         S(2,6)=SHRO(PAO,GHOLD(2))
         IF(S(1,6).LT.WAO .AND. S(2,6).LT.GHOLD(7)) GOTO 75
         IF(S(1,6).LT.WAO) GOTO 73
         IF(S(2,6).LT.GHOLD(7)) GOTO 71
C
C         HAVE BOTH COVERS DRY
         S(1,6)=WAO
         S(1,7)=0.
         S(2,6)=GHOLD(7)
         S(2,7)=0.
         GOTO 22
C
C         HAVE INSIDE COVER WET, OUTSIDE DRY
      71 S(1,6)=WAO
         S(1,7)=0.
         S(2,7)=SW(S(2,6),GHOLD(2))
C         TEST FOR NO COVERS
         IF(TDO.EQ. 1.0 .AND. TDI.EQ. 1.0) GOTO 22
         IF(TDI.EQ. 1.0) GOTO 72
C         HAVE AN INNER COVER AND IT IS WET
         EP(7)=0.96
         EP(5)=EP(6) + TDI*(0.96-EP(6))
```

```
      TRI=0.
      GOTO 22
C      HAVE NO PHYSICAL INNER COVER BUT WET INSIDE
   72 EP(3)=0.96
      EP(1)=EP(2) + TDO*(0.96-EP(2))
      TRO=0.
      GOTO 22
C
C      HAVE OUTSIDE COVER WET, DRY INSIDE
   73 S(1,7)=SW(S(1,6),GHOLD(1))
      S(2,6)=GHOLD(7)
      S(2,7)=0.
C      TEST FOR NO COVERS
      IF(TDO.EQ. 1.0 .AND. TDI.EQ. 1.0) GOTO 22
      IF(TDO.EQ. 1.0) GOTO 74
C      HAVE AND OUTER COVER AND IT IS WET
      EP(1)=0.96
      EP(3)=EP(4) + TDO*(0.96-EP(4))
      TRO=0.
      GOTO 22
C      HAVE NO PHYSICAL OUTER COVER, BUT WET OUTSIDE
   74 EP(5)=0.96
      EP(7)=EP(8) +  TDI*(0.96-EP(8))
      TRI=0.
      GOTO 22
C
C      WET BOTH INSIDE AND OUTSIDE
   75 S(1,7)=SW(S(1,6),GHOLD(1))
      S(2,7)=SW(S(2,6),GHOLD(2))
C      TEST FOR NO COVERS
      IF(TDO.EQ. 1. .AND. TDI.EQ. 1.0) GOTO 22
      IF(TDI.EQ. 1.0) GOTO 77
      IF(TDO.EQ. 1.0) GOTO 76
C      HAVE BOTH COVERS PRESENT AND BOTH ARE WET
      EP(1)=0.96
      EP(3)=EP(4) + TDO*(0.96-EP(4))
      TRO=0.
      EP(5)=EP(6) + TDI*(0.96-EP(6))
      EP(7)=0.96
      TRI=0.
      GOTO 22
C      HAVE NO PHYSICAL OUTER COVER, BOTH SIDES WET
   76 EP(5)=0.96
      EP(7)=0.96
      TRI=0.
      GOTO 22
C      HAVE NO PHYSICAL INNER COVER, BOTH SIDES WET
   77 EP(1)=0.96
      EP(3)=0.96
      TRO=0.
```

```
C
C
C          VEGETATION
   22     S(3,6)=SHRO(PAO,GHOLD(3))
          S(3,7)=SW(S(3,6),GHOLD(3))
          IF(S(3,6).GE.GHOLD(7))GO TO 66
          EP(9)=0.96
C          SOIL
   66     S(4,6)=SHRO(PAO,GHOLD(4))
          S(4,7)=SW(S(4,6),GHOLD(4))
C
          IF(S(4,6).GE.GHOLD(7))GO TO 67
          EP(11)=0.96
C          CURTAIN HEAT EXCHANGER
   67     S(5,6)=SHRO(PAO,GHOLD(5))
          IF(S(5,6).LT.GHOLD(7)) GO TO 61
C          HAVE DRY EXCHANGER SURFACES
          S(5,6)=GHOLD(7)
          S(5,7)=0
          GO TO 62
C          WET EXCHANGER SURFACES
     61   S(5,7)=SW(S(5,6),GHOLD(5))
          EP(13)=.96
C
C   COMPUTE OLD THERMAL RADIATIONS AND SLOPES
   62     T=GHOLD(1) + 273.16
          S(1,4)=4.*GEOM(1)*SB*T**3
          S(1,3)=S(1,4)*T/4.
          T=GHOLD(2) + 273.16
          S(2,4)=4. * GEOM(1)*SB*T**3
          S(2,3)=S(2,4)*T/4.
          T=GHOLD(3) + 273.16
          S(3,4)=4.*GEOM(2)*SB*T**3
          S(3,3)=S(3,4)*T/4.
          T=GHOLD(4) + 273.16
          S(4,4)=4.*GEOM(3)*SB*T**3
          S(4,3)=S(4,4)*T/4.
          T=GHOLD(5)+273.16
          S(5,4)=4.*GEOM(4)*SB*T**3
          S(5,3)=S(5,4)*T/4.
C
C   COMPUTE TRANSFER COEFFICIENTS*AREAS     (*LATENT HEAT)
C   INNER COVER
          LI=HVAP(GHOLD(6))
          CPM=1005. + 1859.*GHOLD(7)
          DT=ABS(GHOLD(6)-GHOLD(2))
          S(2,1)=B(3)*DT**B(4)
          IF(GHOLD(2).GT.GHOLD(6))S(2,1)=S(2,1)/2.
          IF(HPOWR.GT.S(2,1))S(2,1)=HPOWR
          S(2,2)=FKD(S(2,1),GHOLD(7))
```

```
      S(2,1)=S(2,1)*GEOM(1)
      S(2,2)=S(2,2)*GEOM(1)*LI
C  VEGETATION
      DT=ABS(GHOLD(3)-GHOLD(6))
      S(3,1)=B(3)*DT**B(4)
      IF(GHOLD(6).GT.GHOLD(3))S(3,1)=S(3,1)/2.
      IF(HPOWR.GT.S(3,1))S(3,1)=HPOWR
      S(3,2)=0.
      IF(S(3,1).LT.1.E-10)GO TO 23
      S(3,2)=1./((CPM/S(3,1)) + RS)
      IF(S(3,6).LT.GHOLD(7)) S(3,2)=FKD(S(3,1),GHOLD(7))
   23 S(3,1)=S(3,1)*GEOM(2)
      S(3,2)=S(3,2)*GEOM(2)*LI
C  SOIL SURFACE
      DT=ABS(GHOLD(4)-GHOLD(6))
      S(4,1)=B(3)*DT**B(4)
      IF(GHOLD(6).GE.GHOLD(4))S(4,1)=S(4,1)/2.
      IF(HPOWR.GT.S(4,1))S(4,1)=HPOWR
      S(4,2)=1./((CPM/S(4,1)) + RSOIL)
      S(4,1)=S(4,1)*GEOM(3)
      S(4,2)=S(4,2)*GEOM(3)*LI
C       CURTAIN HEAT EXCHANGER
      DT=ABS(GHOLD(5)-GHOLD(6))
      S(5,1)=B(3)*DT**B(4)
      IF(HPOWR.GT.S(5,1))S(5,1)=HPOWR
      S(5,2)=FKD(S(5,1),GHOLD(7))
      S(5,1)=S(5,1)*GEOM(4)
      S(5,2)=S(5,2)*GEOM(4)*LI
C   INFILTRATION
      DT=SQRT(ABS(GHOLD(6)-TAO))
      VIF=B(11)*UAO + B(12)*DT + B(13)
      HIF=VIF*DA*(1.005 + 1.859*WAO)
      KDF=FKD(HIF,WAO)
      HIF=HIF*GEOM(1)
      KDF=KDF*GEOM(1)*LI
C    NATURAL VENTILATION
      VN=B(5)*UAO + B(6)*DT + B(7)
      HIN=(VN/3600.)*GEOM(5)*DA*(1005. + 1859.*WAO)
      KDN=FKD(HIN,WAO)*LI
C  EXTERNAL DEVICE SUMS
      SUMMC=0.
      SUMHX=0.
      IF(JMAX.EQ.0) GOTO 31
      DO 30 J=1,JMAX
      CPAX=1005.+1859.*(GHOLD(7)+WX(J))/2.
      SUMHX=SUMHX + CPAX*TX(J)*MX(J)
      SUMMC=SUMMC + CPAX*MX(J)
   30 CONTINUE
   31 CONTINUE
C
```

```
C  COMPUTE SHORTENING VARIABLES
      S(1,5)=S(1,3)-S(1,4)*GHOLD(1)
      S(2,5)=S(2,3)-S(2,4)*GHOLD(2)
      S(3,5)=S(3,3)-S(3,4)*GHOLD(3)
      S(4,5)=S(4,3)-S(4,4)*GHOLD(4)
      S(5,5)=S(5,3)-S(5,4)*GHOLD(5)
      S(1,8)=S(1,2)*(S(1,6)-S(1,7)*GHOLD(1))
      S(2,8)=S(2,2)*(S(2,6)-S(2,7)*GHOLD(2))
      S(3,8)=S(3,2)*(S(3,6)-S(3,7)*GHOLD(3))
      S(4,8)=S(4,2)*(S(4,6)-S(4,7)*GHOLD(4))
      S(5,8)=S(5,2)*(S(5,6)-S(5,7)*GHOLD(5))
C
C
C      STORE EMITTANCES IN MORE CONVIENT ARRAY
      EPW(1)=EP(3)
      EPW(2)=EP(7)
      EPW(3)=EP(9)
      EPW(4)=EP(11)
      EPW(5)=EP(13)
C
C      COMPUTE REFLECTANCES
      RHO(1)=1.-EPW(1)-TRO
      RHO(2)=1.-EPW(2)-TRI
C      EFFECTIVE REFLECTANCE OF COVER
      RHO(2)=RHO(2)+RHO(1)*TRI**2
      RHO(3)=1.-EPW(3)
      RHO(4)=1.-EPW(4)
      RHO(5)=1.-EPW(5)
C
C      COMPUTE SUMS OF ANGLE FACTOR-REFLECTANCE PRODUCTS AND ADD
C      ANGLE FACTORS
      DO 78 I=2,5
      DO 78 J=2,5
      V(I,J)=AF(I,J)
      DO 78 L= 2,5
      V(I,J)=V(I,J)+AF(I,L)*RHO(L)*AF(L,J)
   78 CONTINUE
C
C
C      COMPUTE UP AND DOWN Y TERMS
      YD=RAO*TRO*TRI+EP(3)*TRI*S(1,5)+EP(7)*S(2,5)
      YU=YD*V(2,2)
      DO 79 J=3,5
   79 YU=YU+EPW(J)*S(J,5)*V(J,2)
C      COMPUTE NET Y RADIATION TERMS
C      ON OUTER COVER
      S(1,9)=EP(1)*(RAO+RGO-S(1,5))
      S(1,9)=S(1,9)+EP(3)*(-S(1,5)+EP(5)*S(2,5)+TRI*YU
     1        +EP(3)*(1.-EP(5)-TRI)*S(1,5))
C      ON INNER COVER
```

```
      S(2,9)=EP(5)*((RAO+RGO)*TRO+EP(3)*S(1,5)-S(2,5)+EP(5)
     1        *RHO(1)*S(2,5))
      S(2,9)=S(2,9)+EP(7)*(YU-S(2,5))
C      ON VEGETATION, SOIL AND EXHCNAGER
      DO 81 I=3,5
      S(I,9)=-S(I,5)+YD*V(2,I)
      DO 80 J=3,5
   80 S(I,9)=S(I,9)+EPW(J)*S(J,5)*V(J,I)
      S(I,9)=S(I,9)*EPW(I)
   81 CONTINUE
C
      IF(TIME.LT.FTRACE .OR. TIME.GT.STRACE) GOTO 132
      WRITE(KOUT,82)(J,J=2,5),(J,J=2,5)
   82 FORMAT(" ANGLE FACTOR MATRIX",22X,"V(I,J) MATRIX"/
     1    1X,"I",4X,4("J=",I1,6X),2X,4("J=",I1,6X))
      DO 83 I=2,5
   83 WRITE(KOUT,84) I,(AF(I,J),J=2,5),(V(I,J),J=2,5)
   84 FORMAT(1H ,I1,4F9.5,2X,4F9.5)
      WRITE(KOUT,91)(I,RHO(I),I=1,5)
   91 FORMAT(" RHO",5(I4,F9.5))
      WRITE(KOUT,92)(I,EPW(I),I=1,5)
   92 FORMAT(" EPW",5(I4,F9.5))
      WRITE(KOUT,201)(I,I=1,5)
  201 FORMAT(" S(I,J) MATRIX"/1X,"J",4X,5("I=",I1,10X))
      DO 202 J=1,9
  202 WRITE(KOUT,203) J,(S(I,J),I=1,5)
  203 FORMAT(1H ,I1,5E13.5)
      WRITE(KOUT,85)YD,YU
  85  FORMAT("  YD=",E13.5,"   YU=",E13.5)
      WRITE(KOUT,86)HIF,KDF,HIN,KDN
  86   FORMAT(" HIF=",E13.5,"  KDF=",E13.5,
     1              "  HIN= ",E13.5,"  KDN=",E13.5)
C
C
C       CHECK IF THIS IS THE FIRST CALL TO CGRNHS FOR THIS TIME STEP
  132 IF(TIME.EQ.GHTIME) GOTO 205
C
C      HAVE FIRST CALL FOR THIS TIME. THEREFORE, NEED TO RESET GHTIME
C      AND SHIFT OLD SOIL TEMPS AND FLUXES.
       GHTIME=TIME
       DO 122 I=2,MMAX
       II=MMAX-I+3
       TGOOLD(II)=TGOOLD(II-1)
       TGSOLD(II)=TGSOLD(II-1)
  122 CONTINUE
       TGOOLD(2)=GHOLD(4)
       TGSOLD(2)=GHOLD(8)
       DO 124 I=1,3
  124 GSOLD(I)=GS(I)
C
```

```
C       COMPUTE SUMS OF PRODUCTS OF SOIL RESPONSE FACTORS AND OLD TEMPERAT
C       FOR THIS TIME
        DO 125 I=1,3
  125 GSUM(I)=0.
        GSUM(4)=BRF(4,1)
        DO 121 I=2,MMAX
        GSUM(1)=GSUM(1) + BRF(1,I)*TGOOLD(I) - BRF(2,I)*TGSOLD(I)
        GSUM(2)=GSUM(2) + BRF(2,I)*TGOOLD(I) - BRF(3,I)*TGSOLD(I)
        GSUM(3)=GSUM(3) + BRF(4,I)*TGSOLD(I)
        GSUM(4)=GSUM(4) + BRF(4,I)
  121 CONTINUE
        GSUM(1)=GSUM(1)*GEOM(3) + BR*GSOLD(1)
        GSUM(2)=GSUM(2)*GEOM(3) + BR*GSOLD(2)
        GSUM(3)=GSUM(3)*GEOM(3)
        GSUM(4)=GSUM(4)*GEOM(3)*TD
C
        IF(TIME.LT.FTRACE .OR. TIME.GT.STRACE) GOTO 205
        WRITE(KOUT,131)
  131 FORMAT("  M",3X,"TGOOLD",3X,"TGSOLD")
        DO 127 I=1,MMAX
  127 WRITE(KOUT,128) I,TGOOLD(I),TGSOLD(I)
  128 FORMAT(1H ,I2,2F9.4)
        WRITE(KOUT,130)(I,GSOLD(I),I=1,3)
  130 FORMAT(" GSOLD",2X,3(I3,E13.5))
        WRITE(KOUT,129)(I,GSUM(I),I=1,4)
  129 FORMAT(" GSUM",3X,4(I3,E13.5))
C
C  FILL IN THE ELEMENTS OF THE A MATRIX
  205 DO  24 I=1,8
        DO 24 J=1,9
   24 A(I,J)=0.
C  OUTER COVER
        A(1,1)=-S(1,4)*EP(1) + S(1,4)*EP(3)*(-1.+EP(3)*(TRI**2)*V(2,2)
     1      + (1.-EP(5)-TRI))
        A(1,1)=A(1,1) - UC - S(1,1) - S(1,2)*S(1,7)
        A(1,2)=S(2,4)*EP(3)*(EP(5) + TRI*EP(7)*V(2,2)) + UC
        A(1,3)=S(3,4)*EPW(3)*EPW(1)*TRI*V(3,2)
        A(1,4)=S(4,4)*EPW(4)*EPW(1)*TRI*V(4,2)
        A(1,5)=S(5,4)*EPW(5)*EPW(1)*TRI*V(5,2)
        A(1,9)= -SCO -S(1,9) - S(1,1)*TAO + S(1,8) - S(1,2)*WAO
C       INNER COVER
        A(2,1)=S(1,4)*EP(3)*(EP(5) + EP(7)*TRI*V(2,2)) + UC
        A(2,2)=S(2,4)*EP(5)*(-1. + EP(5)*RHO(1)) + S(2,4)*EP(7)*
     1    (-1. + EP(7)*V(2,2))
        A(2,2)=A(2,2) - UC -  S(2,1) - S(2,2)*S(2,7)-MXC
        A(2,6)=S(2,1)
        A(2,7)=S(2,2)
        A(2,3)=S(3,4)*EPW(3)*EPW(2)*V(3,2)
        A(2,4)=S(4,4)*EPW(4)*EPW(2)*V(4,2)
        A(2,5)=S(5,4)*EPW(5)*EPW(2)*V(5,2)
```

```
      A(2,9)= -SCI -S(2,9) + S(2,8) -MXC*TXC
C      GREENHOUSE AIR ENTHALPY BALANCE
      A(6,2)=S(2,1) + S(2,2)*S(2,7)
      A(6,6)=-S(5,1) - S(4,1) - S(3,1) - S(2,1) - HIF - HIN - SUMMC
      A(6,7)=-S(5,2) - S(4,2) - S(3,2) - S(2,2) - KDF - KDN - LI*SUMMX
      A(6,3)=S(3,1) + S(3,2)*S(3,7)
      A(6,4)=S(4,1)+S(4,2)*S(4,7)
      A(6,5)=S(5,1)+S(5,2)*S(5,7)
      A(6,9)= -S(5,8) - S(4,8) - S(3,8) - S(2,8)
      A(6,9)=A(6,9) - HIF*TAO - KDF*WAO - HIN*TAO - KDN*WAO
      A(6,9)=A(6,9) - SUMHX - LI*SUMEX-XR*(1.-FR)
C      GREENHOUSE AIR MOISTURE BALANCE
      A(7,2)=S(2,2)*S(2,7)
      A(7,7)=A(6,7)
      A(7,3)=S(3,2)*S(3,7)
      A(7,4)=S(4,2)*S(4,7)
      A(7,5)=S(5,2)*S(5,7)
      A(7,9)=-S(5,8)-S(4,8)-S(3,8)-S(2,8)-KDF*WAO - KDN*WAO - LI*SUMEX
C      VEGETATION
      A(3,1)=EP(9)*EP(3)*TRI*S(1,4)*V(2,3)
      A(3,2)=V(2,3)*EP(9)*S(2,4)*EP(7)
      A(3,6)=S(3,1)
      A(3,7)=S(3,2)
      A(3,3)=S(3,4)*EPW(3)*(-1. + EPW(3)*V(3,3))-S(3,1)-S(3,2)*S(3,7)
      A(3,4)=EPW(4)*V(4,3)*S(4,4)*EP(9)
      A(3,5)=EPW(5)*V(5,3)*EP(9)*S(5,4)
      A(3,9)= -SV -S(3,9) +S(3,8)-XR*FR*GEOM(12)/GEOM(3)
C
C      SOIL SURFACE
      A(4,1)=EP(11)*EP(3)*S(1,4)*V(2,4)*TRI
      A(4,2)=EP(11)*EP(7)*S(2,4)*V(2,4)
      A(4,6)=S(4,1)
      A(4,7)=S(4,2)
      A(4,3)=EPW(3)*V(3,4)*EP(11)*S(3,4)
      A(4,4)=-S(4,1)-S(4,2)*S(4,7)+S(4,4)*EPW(4)*(-1.+EPW(4)*V(4,4))
      A(4,4)=A(4,4) - GEOM(3)*BRF(1,1)
      A(4,5)=EPW(5)*V(5,4)*EP(11)*S(5,4)
      A(4,8)=BRF(2,1)*GEOM(3)
      A(4,9)=-SG-S(4,9)+S(4,8)+GSUM(1)-XR*FR*(GEOM(3)-GEOM(12))/GEOM(3)
C
C      CURTAIN HEAT EXCHANGER
      A(5,1)=EP(13)*EP(3)*TRI*S(1,4)*V(2,5)
      A(5,2)=V(2,5)*EP(13)*S(2,4)*EP(7)
      A(5,3)=EPW(3)*V(3,5)*EP(13)*S(3,4)
      A(5,4)=EPW(4)*V(4,5)*EP(13)*S(4,4)
      A(5,5)= S(5,4)*EPW(5)*(-1. + EPW(5)*V(5,5))
     1           -S(5,1)-S(5,2)*S(5,7)-MXE
      A(5,6)=S(5,1)
      A(5,7)=S(5,2)
      A(5,9)= -S(5,9) + S(5,8) -MXE*TXE
```

```
C
C        SOIL STORAGE DEPTH
       A(8,4)=GEOM(3)*BRF(2,1)
       A(8,8)= -GEOM(3)*(BRF(3,1)+BRF(4,1)) - MXG
       A(8,9)= -GSUM(2) + GSUM(3) - GSUM(4) - MXG*TXG
C
       IF(TIME.LT.FTRACE .OR. TIME.GT.STRACE) GOTO 209
       WRITE(KOUT,206)
  206 FORMAT(" A(I,J) MATRIX"/1X,"J",3X,4("I",15X))
       DO 207 J=1,9
  207 WRITE(KOUT,208) J,(I,A(I,J),I=1,8)
  208 FORMAT(1H ,I1,4(I4,E12.5)/2X,4(I4,E12.5))
C
C        SOLVE FOR UPDATED VALUES OF THE SEVEN UNKNOWNS
C        USE TRIANGULARIZATION WITH BACK SUBSTITUTION
C        SEE CROUT'S METHOD IN C. FROBERG, 1965,
C        INTRODUCTION TO NUMERICAL ANAYSIS,
C        ADDISON-WESLEY PUB. CO., READING, MASS. PP78-81
  209 I9=8
C        TRIANGULARIZE
       DO 104 I5=1, I9
       DO 105 I6=I5, I9
       L8=I5-1
       IF (L8-1) 105, 106, 106
  106 DO 107 I=1, L8
      A(I6,I5)=A(I6,I5) - A(I6,I)*A(I,I5)
  107 CONTINUE
  105 CONTINUE
       L9=I5 + 1
       M1=I9 + 1
       DO 104 K5=L9,M1
       M2=I5-1
       IF(M2.EQ.0) GOTO 111
       DO 109 K6=1,M2
      A(I5,K5)=A(I5,K5) - A(I5,K6)*A(K6,K5)
  109 CONTINUE
  111 IF(ABS(A(I5,I5)).GT. 1.E-20) GOTO 112
      IF(ABS(A(I5,K5)).LT. 1.E-10) GOTO 113
      WRITE(KOUT,114)I5,I5,A(I5,I5),I5,K5,A(I5,K5)
  114 FORMAT(" **WARNING - NEAR ZERO DENOMINATOR IN CGH"/
     1       "A(",I2,",",I2,")=",E14.6/
     2       "A(",I2,",",I2,")=",E14.6)
  113 A(I5,K5)=0.
      GOTO 104
  112 A(I5,K5)=A(I5,K5)/A(I5,I5)
  104 CONTINUE
C
C        BACK SUBSTITUTE
       M3=I9-1
       M4=I9+1
```

```
       DO 110 I5=1,M3
       L9=(M3+1) - I5
       L8=L9+1
       DO 110 I=L8,I9
      A(L9,M4)=A(L9,M4) - A(L9,I)*A(I,M4)
 110  CONTINUE
C
C       DECODE
       DO 25 I=1,8
       GH(I)=A(I,9)
   25 CONTINUE
C
C
C       *** OUTPUTS ***
C
C              OUTER COVER TEMP (C)
       OUTI(1)=GH(1)
C
C              INNER COVER TEMP (C)
       OUTI(2)=GH(2)
C
C              VEGETATION TEMP (C)
       OUTI(3)=GH(3)
C
C              SOIL SURFACE TEMP (C)
       OUTI(4)=GH(4)
C
C       CURTAIN HEAT EXCHANGER TEMP(C)
       OUTI(5)=GH(5)
C
C              INSIDE AIR TEMP (C)
       OUTI(6)=GH(6)
C
C              INSIDE AIR HUMIDITY RATIO (KG/KG)
       OUTI(7)=GH(7)
C
C
C              SOIL STORAGE TEMP (C)
       OUTI(8)=GH(8)
C              SOLAR RADIATION ABSORBED BY OUTER COVER (W)
       OUTI(9)=SCO
C
C       SOLAR ABSORBED BY INNER COVER(W)
       OUTI(10)=SCI
C              SOLAR RADIATION ABSORBED BY VEGETATION (W)
       OUTI(11)=SV
C
C              SOLAR RADIATION ABSORBED BY SOIL (W)
       OUTI(12)=SG
C
```

```
C
C
C       NET THERMAL RADIATION
C       FIRST UPDATE BLACK BODY VALUES
        DO 87 I=1,5
        J=I-1
        IF(I.EQ.1)J=1
C
   87   S(I,3)=(SB*(GH(I)+273.16)**4)*GEOM(J)
C       COMPUTE UP AND DOWN RADIATION
        YD=RAO*TRO*TRI+EPW(1)*TRI*S(1,3)+EPW(2)*S(2,3)
        YU=YD*V(2,2)
        DO 88 J=3,5
   88   YU=YU + EPW(J)*S(J,3)*V(J,2)
C       OUTER COVER
        OUTI(13)=EP(1)*(RAO+RGO-S(1,3))
        OUTI(13)=OUTI(13)+EP(3)*(-S(1,3)+EP(5)*S(2,3)+TRI*YU
     1          +EP(3)*(1.-EP(5)-TRI)*S(1,3))
C       INNER COVER
        OUTI(14)=EP(5)*((RAO+RGO)*TRO + EP(3)*S(1,3)-S(2,3)
     1          +EP(5)*RHO(1)*S(2,3))
        OUTI(14)=OUTI(14)+EP(7)*(YU-S(2,3))
C       VEGETATION, SOIL, AND EXCHANGER
        DO 89 I=3,5
        L=I+12
        OUTI(L)=-S(I,3) +YD*V(2,I)
        DO 90 J=3,5
   90   OUTI(L)=OUTI(L) + EPW(J)*S(J,3)*V(J,I)
        OUTI(L)=OUTI(L)*EPW(I)
   89   CONTINUE
C               UPDATE HUMIDITY RATIOS
        DO 32 I=1,5
     32 S(I,6)=S(I,6) + S(I,7)*(GH(I)-GHOLD(I))
C
C               SENSIBLE AND LATENT HEAT FROM OUTER COVER (W)
        OUTI(18)=S(1,1)*(GH(1)-TAO)
        OUTI(19)=S(1,2)*(S(1,6)-WAO)
C
C               SENSIBLE AND LATENT HEAT TO INNER COVER (W)
        OUTI(20)=S(2,1)*(GH(6)-GH(2))
        OUTI(21)=S(2,2)*(GH(7)-S(2,6))
C
C               SENSIBLE AND LATENT HEAT FROM VEGETATION TO AIR (W)
        OUTI(22)=S(3,1)*(GH(3)-GH(6))
        OUTI(23)=S(3,2)*(S(3,6)-GH(7))
C
C               SENSIBLE AND LATENT HEAT FROM SOIL TO AIR (W)
        OUTI(24)=S(4,1)*(GH(4)-GH(6))
        OUTI(25)=S(4,2)*(S(4,6)-GH(7))
C
```

```
C      SENSIBLE AND LATENT HEAT FROM CURTAIN HEAT EXCHANGER TO AIR
      OUTI(26)=S(5,1)*(GH(5)-GH(6))
      OUTI(27)=S(5,2)*(S(5,6)-GH(7))
C             SENSIBLE AND LATENT HEAT FROM INSIDE AIR TO OUTSIDE AIR
C             DUE TO INFILTRATION (W)
      OUTI(28)=HIF*(GH(6)-TAO)
      OUTI(29)=KDF*(GH(7)-WAO)
C
C             SENSIBLE AND LATENT HEAT FROM INSIDE TO OUTSIDE DUE
C             TO NATURAL VENTILATION THROUGH VENTILATORS
      OUTI(30)=HIN*(GH(6)-TAO)
      OUTI(31)=KDN*(GH(7)-WAO)
C
C             CONDUCTION FROM INNER TO OUTER COVER (W)
      OUTI(32)=UC*(GH(2)-GH(1))
C
C             SURFACE SOIL HEAT FLUX (W)
      OUTI(33)=GEOM(3)*(BRF(1,1)*GH(4) - BRF(2,1)*GH(8)) + GSUM(1)
C
C      SOIL HEAT FLUX LEAVING BOTTOM OF UPPER LAYER (W)
      OUTI(34)=GEOM(3)*(BRF(2,1)*GH(4) - BRF(3,1)*GH(8)) + GSUM(2)
C
C      SOIL HEAT FLUX ENTERING TOP OF BOTTOM SEMI-INFINITE REGION(W)
      OUTI(35)=GEOM(3)*BRF(4,1)*GH(8) + GSUM(3) - GSUM(4)
C
C      SENSIBLE HEAT ADDED TO COVER FROM EXTERNAL DEVICE(W)
C      FLUID EXIT TEMP(C), AND FLOW RATE(KG/S)
      OUTI(37)=MXC*(TXC-GH(2))
      OUTI(38)=GH(2)-(TXC-GH(2))
      OUTI(39)=XIN(17)
C
C      SENSIBLE HEAT ADDED TO SOIL STORAGE FROM EXTERNAL DEVICE(W)
C      FLUID EXIT TEMP(C), AND FLOW RATE(KG/S)
      OUTI(40)=MXG*(TXG-GH(8))
      OUTI(41)=GH(8)-(TXG-GH(8))
      OUTI(42)=XIN(19)
C
C      SENSIBLE HEAT ADDED TO CURTAIN HEAT EXCHANGER FORM EXTERNAL DEVICE
C      FLUID EXIT TEMP(C) AND FLOW RATE(KG/S)
      OUTI(43)=MXE*(TXE-GH(5))
      OUTI(44)=GH(5)-(TXE-GH(5))
      OUTI(45)=XIN(21)
C
C      ENERGY OUTPUT FROM INFRARED HEATER(W)
      OUTI(46)=XR
C
C      SENSIBLE AND LATENT HEAT ADDED TO GREENHOUSE AIR BY EXTERNAL DEVIC
      IF(JMAX.EQ.0) GOTO 18
      DO 18 J=1,JMAX
      JO=47 + (J-1)*3
```

```
      OUTI(JO+2)=MX(J)*LI*(WX(J)-GH(7))
      OUTI(JO+1)=MX(J)
      OUTI(JO)=MX(J)*(TX(J)-GH(6))*(1005.+1859.*(GH(7)+WX(J))/2.)
   18 CONTINUE
C
C
C       OVERALL COEFFICIENT OF HEAT TRANSMISSION - U (W/M2/C)
      OUTI(36)=-1
      IF(ABS(GH(6) - TAO) .LT. .1) GOTO 17
      OUTI(36)=SV+SG-OUTI(33)-OUTI(30)-OUTI(31)+OUTI(37)+OUTI(43)+XR
      IF(JMAX.EQ.0) GOTO 19
      DO 19 J=1,JMAX
      JO=47 + (J-1)*3
      OUTI(36)=OUTI(36) + OUTI(JO) + OUTI(JO+2)
  19  CONTINUE
      OUTI(36)=OUTI(36)/(GEOM(1)*(GH(6)-TAO))
   17 CONTINUE
C
C       UPDATE OLD VALUES AND STORE IN COMMON
      DO 63 I=1,8
   63 GHOLD(I)=GH(I)
      GS(1)=OUTI(33)
      GS(2)=OUTI(34)
      GS(3)=OUTI(35)
C
       RETURN
      END
```

Appendix D: Coding forms for input file MEBDI

MODULAR ENERGY BALANCE MODEL INPUT DATA (MEBDI)

RUN TITLE:

WEATHER FILE:

OUTPUT FILE:

YR(2)	STARTING MON	TIME DAY	HR(.)	TIME INCRE	NO. TIMES	FIRST TRACE	LAST TRACE

NO. UNITS :

UNIT		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	TYPE:														
	PAR :														
	IN :														
	OUT :														
	T :														
2	TYPE:														
	PAR :														
	IN :														
	OUT :														
	T :														
3	TYPE:														
	PAR :														
	IN :														
	OUT :														
	T :														
4	TYPE:														
	PAR :														
	IN :														
	OUT :														
	T :														
5	TYPE:														
	PAR :														
	IN :														
	OUT :														
	T :														
6	TYPE:														
	PAR :														
	IN :														
	OUT :														
	T :														
7	TYPE:														
	PAR :														
	IN :														
	OUT :														
	T :														

Form for units 1 through 7 of file MEBDI.

MEB MODEL INPUT DATA - CONTINUED

UNIT		1	2	3	4	5	6	7	8	9	10	11	12	13	14
8	TYPE:														
	PAR :														
	IN :														
	OUT :														
	T :														
9	TYPE:														
	PAR :														
	IN :														
	OUT :														
	T :														
10	TYPE:														
	PAR :														
	IN :														
	OUT :														
	T :														
11	TYPE:														
	PAR :														
	IN :														
	OUT :														
	T :														
12	TYPE:														
	PAR :														
	IN :														
	OUT :														
	T :														
13	TYPE:														
	PAR :														
	IN :														
	OUT :														
	T :														
14	TYPE:														
	PAR :														
	IN :														
	OUT :														
	T :														
15	TYPE:														
	PAR :														
	IN :														
	OUT :														
	T :														
16	TYPE:														
	PAR :														
	IN :														
	OUT :														
	T :														

PRINTER: b---b---b---b---b---b---b---b---b---b---b---b---b---b---b---

LABELS: b---b---b---b---b---b---b---b---b---b---b---b---b---b---b---

Form for units 8 through 16 of file MEBDI.

MEB MODEL INPUT DATA - CONTINUED

UNIT 1 2 3 4 5 6 7 8 9 10 11 12 13 14

TYPE: ,
PAR: , , , , , , , , , , , , ,
IN: ,
OUT: , , , , , , , , , , , , ,
T: , , , , , , , , , , , , ,

TYPE: ,
PAR: , , , , , , , , , , , , ,
IN: ,
OUT: , , , , , , , , , , , , ,
T: , , , , , , , , , , , , ,

TYPE: ,
PAR: , , , , , , , , , , , , ,
IN: ,
OUT: , , , , , , , , , , , , ,
T: , , , , , , , , , , , , ,

TYPE: ,
PAR: , , , , , , , , , , , , ,
IN: ,
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PRINTER: b---b---b---b---b---b---b---b---b---b---b---b---b---b---
LABELS: b---b---b---b---b---b---b---b---b---b---b---b---b---b---

Blank form for file MEBDI.

TYPE 5 GREENHOUSE

UNIT No.:

PARAMETERS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
N_p	J	M	n	A_c	A_g	A_w	v_{ai}	C_{xc}	C_{xg}	ρ_{vg}	b_1	b_2	U_w	$\tau_{s\,00}$	$\tau_{s\,01}$
17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
$\tau_{s\,10}$	$\tau_{s\,11}$	$\alpha_{s\,00}$	$\alpha_{s\,01}$	$\alpha_{s\,10}$	$\alpha_{s\,11}$	$h_{ai\,0}$	$h_{ai\,1}$	$h_{f\,0}$	$h_{f\,1}$	$h_{co\,0}$	$h_{co\,1}$	$h_{ci\,0}$	$h_{ci\,1}$	$b_{3\,0}$	$b_{3\,1}$
33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
$b_{4\,0}$	$b_{4\,1}$	$b_{5\,00}$	$b_{5\,01}$	$b_{5\,10}$	$b_{5\,11}$	b_6	b_7	$b_{8\,0}$	$b_{8\,1}$	b_9	b_{10}	b_{11}	b_{12}	b_{13}	r_g
49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64
T_B	k_B	k_1	C_{A1}	k_2	C_{A2}	k_3	C_{A3}	k_4	C_{A4}	k_5	C_{A5}	k_6	C_{A6}	k_7	C_{A7}

INPUTS

1	2	3	4	5	6	7	8
S_o	U_{ao}	P_{ao}	T_{ao}	W_{ao}	L	γ_f	γ_c
9	10	11	12	13	14	15	16
γ_p	γ_N	T_{xc}	M_{xc}	T_{xg}	M_{xg}	T_{x1}	M_{x1}
17	18	19	20	21	22	23	24
W_{x1}	T_{x2}	M_{x2}	W_{x2}	T_{x3}	M_{x3}	W_{x3}	

INITIAL OUTPUTS GUESSES

1	2	3	4 THROUGH $22 + M + (3 * J)$
T_{ai}	W_{ai}	T_c	

USUALLY ALL 1's SEPARATED BY COMMAS

INITIAL SOIL TEMPERATURES

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
T_{g1}	T_{g2}	T_{g3}	T_{g4}	T_{g5}	T_{g6}	T_{g7}	T_{g8}	T_{g9}	T_{g10}	T_{g11}	T_{g12}	T_{g13}	T_{g14}	T_{g15}	T_{g16}

Form for type 5 greenhouse input data.

TYPE 14 COMPLICATED GREENHOUSE DATA

Unit No:

Parameters

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
J	A_c	A_g	v_{ai}	l	s	Ne	x_e	ρ_v	ρ_g	ϵ_v	ϵ_g	ϵ_c	C_{xc}	C_{xg}	C_{xe}
17	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**
b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9	b_{10}	r_g	h_{p1}	X_{RM}	f	τ_{sco0}	τ_{sco1}
33	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**
← τ_{Sci} →				← α_{Sco} →		← α_{Sci} →				← U_c →				← τ_{Rco} →	
00	01	10	11	0	1	00	01	10	11	00	01	10	11	0	1
49	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**
← τ_{Rci} →				← ϵ_{coo} →		← ϵ_{coi} →		← ϵ_{cio} →				← ϵ_{cii} →			
00	01	10	11	0	1	0	1	00	01	10	11	00	01	10	11
65	**66**	**67**	**68**	**69**	**70**	**71**	**72**	**73**	**74**	**75**	**76**				
← b_{11} →				← b_{12} →				← b_{13} →							
00	01	10	11	00	01	10	11	00	01	10	11				

Inputs

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
S_o	R_{ao}	u_{ao}	P_{ao}	T_{ao}	W_{ao}	y	w
9	**10**	**11**	**12**	**13**	**14**	**15**	**16**
γ_f	γ_{co}	γ_{ci}	γ_p	γ_N	γ_e	γ_R	T_{xc}
17	**18**	**19**	**20**	**21**	**22**	**23**	**24**
M_{xc}	T_{xg}	M_{xg}	T_{xe}	M_{xe}	T_{x1}	M_{x1}	W_{x1}
25	**26**	**27**	**28**	**29**	**30**		
T_{x2}	M_{x2}	W_{x2}	T_{x3}	M_{x3}	W_{x3}		

Initial Output Guesses

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
T_{co}	T_{ci}	T_v	T_{go}	T_e	T_{ai}	W_{ai}	T_{gs}

9 through **46+3*J** are usually all 1's separated by comma-blank

Continue on form for surface layer soil heat conduction transfer functions

Form for type 14 complicated greenhouse input data.

TYPE 14 COMPLICATED GREENHOUSE DATA—Continued

Soil Heat Conduction Transfer Functions and Temperature History

M	$G_{O,to-1}$	$G_{so,to-1}$	Upper Slab Description

B_r	T_d	B_{41}	Lower Semi-infinite Description

m	B_{1m}	B_{2m}	B_{3m}	$T_{go,to-m+1}$	$T_{gs,to-m+1}$	Time*
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						
21						
22						
23						
24						

*Not used

Form for soil heat conduction transfer functions and temperature history of type 14 complicated greenhouse.

TYPE 15 SIMPLE GREENHOUSE DATA

UNIT No.:

PARAMETERS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
J	A_c	A_g	v_{ai}	f_λ	b_{20}	b_{30}	b_{21}	b_{31}	U_{Max}	η	ρ_{vg}	τ_{s0}	b_{00}	b_{10}	τ_{s1}

17	18
b_{01}	b_{11}

INPUTS

1	2	3	4	5	6	7	8
S_o	U_{ao}	P_{ao}	T_{ao}	T_{wb}	γ_c	γ_p	γ_N
9	10	11	12	13	14	15	16
T_{x1}	M_{x1}	T_{x2}	M_{x2}	T_{x3}	M_{x3}	T_{x4}	M_{x4}

INITIAL OUTPUT GUESSES

1	2	3	4	5	6
T_{ai}	S_i	ΣX_j	C	V_s	V

2 THROUGH 6 CAN USUALLY BE 1's

Form for type 15 simple greenhouse input data.

Type 1 Reader (READR)

PARAMETERS - 0
INPUTS - 0
OUTPUTS - 23
DERIVATIVES - 0

No.	Item	Test Values[1/]
OUTPUTS:		
1.	Year (last two digits)	78
2.	Month	3
3.	Day	7
4.	Hour (can use fractional hours)	0.0
5.	Dew point (°C)	10.5
6.	Humidity ratio (kg H_2O/kg air)	0.00818
7.	Windspeed (m/s)	2.51
8.	Station pressure (kPa)	97.91
9.	Dry bulb temperature (°C)	12.9
10.	Wet bulb temperature (°C)	11.5
11.	Relative humidity (%)	85
12.	Total solar radiation on horizontal surface (W/m^2)	0
13.	Diffuse solar radiation on horizontal surface (W/m^2)	0
14.	Incidence angle on horizontal surface (deg)	90
15.	Total solar radiation on vertical surface (W/m^2)	0
16.	Diffuse solar radiation on vertical surface (W/m^2)	0
17.	Incidence angle on vertical surface (deg)	90
18.	Total solar radiation on latitude + 10° surface (W/m^2)	0

Type 1 Reader (Contd)

No.	Item	Test Values[1/]
19.	Diffuse solar radiation on latitude + 10° surface (W/m^2)	0
20.	Incidence angle on latitude + 10° surface (deg)	90
21.	Thermal sky radiation (W/m^2)	[2/]319
22.	8-14 μm sky radiation (W/m^2)	[2/]70
23.	Cloud cover (fraction)	0.00

1/ Data are for 00:00, 7 March 1978, Phoenix, Arizona, as recorded by the National Weather Service.

2/ Calculated following Idso (1981)

Type 2 Integrator (INGTR)

PARAMETERS - 3
INPUTS - up to 40
OUTPUTS - up to 40
DERIVATIVES - 0

No.	Symbol	Item	Test Values[1]
PARAMETERS:			
1.	N	Number of inputs	1
2.	t	Elapsed time between resetting (hr)	24
3.	N_u	Unit number (needed by MEB to identify accumulators when more than one Type 2 Integrators are used)	7
INPUTS:			
1.	X_1	First input to be integrated	1.15459E-4
2.	X_2	Second input to be integrated	-
N.	X_N	Last input to be integrated	-
OUTPUTS:			
1.	Y_1	Integrated value of first input	0.727683
2.	Y_2	Integrated value of second input	-
N.	Y_N	Integrated value of last input	0.00

[1] Input 1 and Output 1 for the previous time step were 1.06159E-4 and 0.328770, respectively, and the time step size was 3600 seconds. These values are from Time 2 of the Simple Conventional Greenhouse example.

Type 3 Printer[1] (PRNTR)

PARAMETERS - 4
INPUTS - up to 40
OUTPUTS - 0
DERIVATIVES - 0

No.	Symbol	Item	Test Values[1]
PARAMETERS:			
1.	N	Total number of inputs	12
2.	t	Elapsed time between printouts (hr)	1
3.	N_c	Number of characters per line of the printer	80
4.	N_u	Unit number for particular simulation (allows more than one Type 3 Printer per simulation)	8
INPUTS:[2]			
1.	X_1	First input to be printed	78
2.	X_2	Second input to be printed	3
.	.		
.	.		
.	.		
N,	X_N	Last input to be printed	0

---

[1] See the Simple Conventional Greenhouse Example.

[2] The X's are labeled with a 3-character mnemonic supplied by the user in File MEBDI (See the "Instructions for Use" section).

Type 4 Thermostat (TSTAT)

PARAMETERS - 3
INPUTS - 2
OUTPUTS - 2
DERIVATIVES - 0

No.	Symbol	Item	Test Values[1/]
PARAMETERS:			
1.	T_s	Set-point temperature (°C)	2
2.	N_u	Unit number for particular simulation (allows more than one Type 4 Thermostat per simulation)	10
3.	Mode	1 for absolute, 2 for differential	2
INPUTS:			
1.	T_1	Temperature (°C) (or other variable)	24.9981
2.	T_2	Temperature. If Mode = 2, differential is computed as $T_1 - T_2$.	22.8452
OUTPUTS:			
1.	γ_1	0.0 if $T_1 > T_s$; 1.0 if $T_1 < Ts$; if T_1 equals or nearly equals T_s, an intermediate value between 0 and 1 is computed. See detailed explanation in Type 4 Thermostat section. Use this output for turning on heaters. If mode = 2, $T_1 - T_2$ is used in the above criteria in place of T_1.	0.577962
2.	γ_2	$1 - \gamma_1$ Use this output for turning on coolers.	0.422038

1/ The values of Inputs 1 and 2 and Output 1 from the previous iteration were 24.9990, 22.6512, and 0.582289. The next previous iteration was 0.587808.

Type 5 Greenhouse (GH)

PARAMETERS - 50 + 2 * No. of soil layers
INPUTS - 14 + 3 * No. of external devices that add energy to the greenhouse air
OUTPUTS - 22 + No. of soil layers + 3 * No. of external devices that add energy to the greenhouse air
DERIVATIVES - No. of soil layers

No.	Math Symbol	Program Symbol	Item	Test Values1/
PARAMETERS:				
1.	-	NP	No. of parameters (50 + 2 * no. of soil layers)	56
2.	J	JMAX	No. of external devices which remove or add) sensible and/or latent heat from greenhouse air	2
3.	M	MMAX	No. of soil layers	3
4.	n	N	Index no. of soil layer that receives energy from external device (set M = 0 if no layer receives external energy)	0
5.	A_c	AC	Area of cover (m^2)	67
6.	A_g	AG	Area of soil (m^2)	27
7.	A_w	AW	Area of wall which has constant properties (m^2)	3/9
8.	V_{ai}	VAI	Volume of air in greenhouse (m^3)	73
9.	c_{xc}	CXC	Heat capacity of fluid that carries energy to cover (J/kg·C)	0
10.	c_{xg}	CXG	Heat capacity of fluid that carries n^{th} soil layer (J/kg·C)	0
11.	ρ_{vg}	RHOV	Reflectance of soil and/or vegetation for solar radiation	0.13
12.	b_1	B(1)	Coefficients in Equation 5-19 for the outside heat transfer coefficient for convection plus thermal radiation	2/17
13.	b_2	B(2)	$h_{ao} = b_1 + b_2 * u_{ao}$ (h_{ao} in $W/m^2 \cdot C$ and u_{ao} in m/s)	2/5.1

Type 5 Greenhouse (Cont'd)

No.	Math Symbol	Program Symbol	Item	γ_f	γ_c	γ_p	Test Values[1/]
14.	U_w	UW	Overall heat transfer coefficient in Equation 5-16 for unchanging wall ($W/m^2 \cdot C$)				[3/]7

Parameters 15 through 42 must correspond to particular values of the control variables for fluid flow, γ_f, cover, γ_c, and powered circulation, γ_p.

No.	Math Symbol	Program Symbol	Item	γ_f	γ_c	γ_p	Test Values
15.	τ_{S00}	TAUS	Transmittance of cover for solar radiation	0	0	-	0.66
16.	τ_{S01}	TAUS		0	1	-	0
17.	τ_{S10}	TAUS		1	0	-	0
18.	τ_{S11}	TAUS		1	1	-	0
19.	α_{S00}	ALPH	Absorptance of cover for solar radiation	0	0	-	0.28
20.	α_{S01}	ALPH		0	1	-	0
21.	α_{S10}	ALPH		1	0	-	0
22.	α_{S11}	ALPH		1	1	-	0
23.	h_{ai0}	HAI	Inside air heat transfer coefficient in Equation 5-20 ($W/m^2 \cdot C$)	-	-	0	[4/]14
24.	h_{ai1}	HAI		-	-	1	[4/]14
25.	h_{f0}	HF	Fluid heat transfer coefficient in Equation 5-21 ($W/m^2 \cdot C$)	0	-	-	10000
26.	h_{f1}	HF		1	-	-	10000
27.	h_{co0}	HCO	Thermal conductance for inner cover material ($W/m^2 \cdot C$)	-	0	-	[5/]272
28.	h_{co1}	HCO		-	1	-	0
29.	h_{ci0}	HCI	Thermal conductance for outer material ($W/m^2 \cdot C$)	-	0	-	[5/]272

No.	Math Symbol	Program Symbol	Item	γ_f	γ_c	γ_p	Test Values[1]
30.	h_{ci1}			-	1	-	0
31.	b_{30}	B(3)	Coefficients for infiltration Equation 5-27 for velocity of air passing through cover	-	0	-	[6]0.12
32.	b_{31}			-	1	-	0
33.	b_{40}	B(4)	$u_{cI} = b_3\, u_{ao} + b_4 \sqrt{\lvert T_{ai}^{old} - T_{ao} \rvert} + b_5$	-	0	-	[6]0.39
34.	b_{41}			-	1	-	0
35.	b_{500}	B(5)	(u_{cI} in mm/s, u_{ao} in m/a, and T_{ai} and T_{ao} in C	-	0	0	0
36.	b_{501}			-	0	1	[6]0.23
37.	b_{510}			-	1	0	0
38.	b_{511}			-	1	1	0
39.	b_6	B(6)	Coefficients for infiltration Equation 5-36 for velocity of air passing	-	-	-	[6]0.12
40.	b_7	B(7)	through unchanging wall, doors, etc.	-	-	-	[6]0.039
41.	b_{80}	B(8)	$u_{wI} = b_6\, u_{ao} + b_7 \sqrt{\lvert T_{ai}^{old} - T_{ao} \rvert} + b_8$	-	-	0	0
42.	b_{81}			-	-	1	[6]0.23
43.	b_9	B(9)	Coefficients for natural ventilation Equation 5-42				[7]9.0
44.	b_{10}	B(10)	$u_N = (b_9\, u_{ao} + b_{10} \sqrt{\lvert T_{ai}^{old} - T_{ao} \rvert})\gamma_N$ u_N in volumes/hr, u_{ao} in m/s, T_{ai}^{old} in C)				[7]4.5
45.	b_{11}	B(11)	Coefficients in Equation 5-58 for leaf stomatal resistance (r_v in m^2s/kg)				[8]100
46.	b_{12}	B(12)					[8]20300
47.	b_{13}	B(13)	$r_v = b_{11} + b_{12}/(S_o \tau_S + b_{13})$				[8]17

Type 5 Greenhouse (Cont'd)

No.	Math Symbol	Program Symbol	Item	Test Values[1/]
48.	r_g	RG	Soil surface resistance to evaporation (0 for wet surface, 10000. for dry) (m^2s/kg)	[9/]100
49.	T_B	TI(MMAX+1)	Deep soil temperature (C)	[10/]21
50.	k_B	K(MMAX+1)	Deep soil thermal conductance ($W/m^2 \cdot C$)	[10/]6.25
51.	k_1	K(1)	Thermal conductance of top soil layer ($W/m^2 \cdot C$)	[10/]11
52.	c_{A1}	C(1)	Thermal capacitance of top soil layer plus thermal capacitance of 1/2 of second ($MJ/m^2 \cdot C$)	[10/]0.2
53.	k_2	K(2)	Thermal conductance of second layer of soil ($W/m^2 \cdot C$)	[10/]25.0
54.	c_{A2}	C(2)	Thermal capacitance of 1/2 of second soil layer plus 1/2 of third ($MJm^2 \cdot C$)	[10/]0.3
55.	k_3	K(3)	Thermal conductance of third layer of soil ($W/m^2 \cdot C$)	[10/]12.5
56.	c_{A3}	C(3)	Thermal capacitance of 1/2 of third soil layer plus 1/2 of fourth ($MJ/m^2 \cdot C$)	[10/]0.6
etc.	etc.	etc.	etc.	

INPUTS:

No.	Math Symbol	Program Symbol	Item	Test Values
1.	S_o	SO	Total downcoming solar radiation outside (W/m^2 of land area)	0
2.	u_{ao}	UAO	Outside windspeed (m/s)	2.51
3.	P_{ao}	PAO	Outside barometric pressure (kPa)	97.91
4.	T_{ao}	TAO	Outside air temperature (C)	12.9
5.	W_{ao}	WAO	Outside humidity ratio (kg/kg)	0.00818
6.	L	LAI	Leaf area index	[8/]2.0
7.	γ_f	GAMF	Control variable for fluid flow in cover (0 for no flow to 1 for max flow)	0

Type 5 Greenhouse (Cont'd)

No.	Math Symbol	Program Symbol	Item	Test Values[1]
8.	γ_c	GAMC	Control variable for cover properties (0 to 1) $p = p_0(1 - \gamma_c) + p_1\gamma_c$	0
9.	γ_p	GAMP	Control variable for powered air circulation (0 for off to 1 for max on)	1
10.	γ_N	GAMN	Control variable for natural ventilation (0 for shut to 1 for max open)	0
11.	T_{xc}	TXC	Temperature of fluid from external device going to cover (C)	0
12.	M_{xc}	MXC	Mass flow rate of fluid from external device going to cover (kg/s)	0
13.	T_{xg}	TXG	Temperature of fluid from external device going to the n^{th} soil layer (C)	0
14.	M_{xg}	MXG	Mass flow rate of fluid from external device going to the n^{th} soil layer (kg/s)	0
15.	T_{x1}	TX(1)	Temperature from External Device 1 (C) going to greenhouse air	22.7097
16.	M_{x1}	MX(1)	Mass flow rate from External Device 1 (kg/s) going to greenhouse air	0.26
17.	W_{x1}	WX(1)	Humidity ratio from External Device (kg/kg) going to greenhouse air	0.0107102
18.	T_{x2}	TX(2)	Temperature from External Device 2 (C)	12.9
19.	M_{x2}	MX(2)	Mass flow rate from External Device 2 (kg/s)	0
20.	W_{x2}	WX(2)	Humidity ratio from External Device 2 (kg/kg)	0
21.	T_{x3}	TX(3)	Temperature from External Device 3 (C)	-
etc.	etc.	etc.	etc.	
OUTPUTS:				
1.	T_{ai}	TAI	Greenhouse air temp (C)	15.4941

Type 5 Greenhouse (Cont'd)

No.	Math Symbol	Program Symbol	Item	Test Values[1]
2.	W_{ai}	WAI	Greenhouse air humidity ratio (kg/kg)	0.0107056
3.	T_c	TC	Greenhouse cover temperature (C)	13.7605
4.	S_i	SI	Solar radiation absorbed by greenhouse (W)	0
5.	S_c	SC	Solar radiation absorbed by cover (W)	0
6.	C_o	OUTI(6)	Convection and thermal radiation from cover to outside (W)	1544.41
7.	C_i	OUTI(7)	Convection and thermal radiation from inside to cover (W)	1544.42
8.	I_{cH}	OUTI(8)	Infiltration of sensible heat through cover (W)	126.208
9.	I_{cE}	OUTI(9)	Infiltration of latent heat through cover (W)	295.412
10.	N_H	OUTI(10)	Natural ventilation of sensible heat (W)	0
11.	N_E	OUTI(11)	Natural ventilation of latent heat (W)	0
12.	C_w	OUTI(12)	Convection, conduction, and thermal radiation through wall (W)	163.428
13.	I_{wH}	OUTI(13)	Infiltration of sensible heat through wall (W)	15.159
14.	I_{wE}	OUTI(14)	Infiltration of latent heat through wall (W)	35.482
15.	G_1	OUTI(15)	Surface soil heat flux (W)	-254.35
16.	E_T	OUTI(16)	Evapotranspiration (kg/s)	0.133083E-3
17.	X_c	OUTI(17)	Sensible heat added to cover from external device (W)	0
18.	-	OUTI(18)	Cover fluid exit temp (C)	27.521

Type 5 Greenhouse (Cont'd)

No.	Math Symbol	Program Symbol	Item	Test Values[1]
19.	M_{xc}	OUTI(19)	Mass flow rate of the cover fluid (kg/s)	0
20.	X_g	OUTI(20)	Sensible heat added to n^{th} soil layer from external device (W)	0
21.	-	OUTI(21)	Soil layer fluid exit temp (C)	0
22.	M_{xg}	OUTI(22)	Mass flow rate of fluid from n^{th} soil layer (kg/s)	0
23.	T_{g1}	TI(1)	Top soil layer temperature (C)	16.3505
24.	T_{g2}	TI(2)	Second soil layer temperature (C)	17.8276
.	.	.		
.	.	.		
.	.	.		
22+M	T_{gM}	TI(MMAX)	Deepest soil layer temperature (C) (M is the number of soil layers)	18.9801
23+M	X_{H1}	OUTI(M+23)	Sensible heat added to greenhouse air by External Device 1 (W)	1922.79
24+M	M_{x1}	MX(1)	Flow rate of External Device 1 (kg/s)	0.26
25+M	X_{E1}	OUTI(M+25)	Latent heat added to greenhouse air by External Device 1 (W)	2.97
26+M	X_{H2}	OUTI(M+26)	Sensible heat added to greenhouse air by External Device 2 (W)	0
27+M	M_{x2}	MX(2)	Flow rate of External Device 2 (kg/s)	0
28+M	X_{E2}	OUTI(M+28)	Latent heat added by External Device 2 (W)	0
etc.	etc.	etc.	etc.	

DERIVATIVES (INITIAL VALUES OF DEPENDENT VARIABLES):[11]

No.	Math Symbol	Program Symbol	Item	Test Values
1.	T_{g1}		Top soil layer temperature (C)	16
2.	T_{g2}		Second soil layer temperature (C)	18
.	.			
.	.			
.	.			
M.	T_{gM}		Deepest soil layer temperature (C)	19

1/ Data were from 00:00, 7 March 1978, at Phoenix, Arizona. The parameters define a small fiberglass greenhouse with sand for soil and tomatoes for the crop. It is connected to a Type 16 Heater and a Type 18 Evaporative Cooler. The values of T_{ai}^{old}, W_{ai}^{old}, and T_c from the previous iteration were 15.5003, 0. 0107102, and 13.7626, respectively.

2/ ASHRAE (1972, p. 357) lists values of b_1 and b_2 of 11 and 3.4, respectively. However, these ASHRAE values are for a smooth surface facing surroundings at the same temperature of the air. To account for a corrugated surface which sees a portion of cold sky, the ASHRAE values were increased 50 percent, to 17 and 5.1 for b_1 and b_2, respectively.

3/ North gable wall is metal spray chamber from eave height to ground.

4/ ASHRAE (1972, p. 357) lists a value of 9.3 $W/m^2 \cdot C$ for the upward surface conductance in still air of a smooth surface seeing surroundings at air temperature. To account for the fact that this is a rough vegetative surface which views a colder roof with an angle factor (see discussion of Type 14 Greenhouse) of about 1.5 and that circulation fans are used in the USWCL greenhouses which cause an average air movement of about 0.3 m/s, the ASHRAE value was increased 50 percent to 14. Use of higher inside and outside2/ transfer coefficients results in an overall inside-to-outside heat transfer coefficient of about 9 $W/m^2 \cdot C$, which is close to measured greenhouse values.

5/ Based on thermal conductivity of 0.159 $W/m \cdot C$ and a half thickness of 0.585 mm for Sol-lite with Tedlar from National Greenhouse Company.

6/ CO_2 infiltration tests done on 3 August 1978 with the USWCL fiberglass greenhouses gave an average b_3 value of 0.12 (mm/s)/(m/s) for the closed greenhouse. The house (#2) which had only evaporative cooler pads to close the air intake gave a value of 0.71. Small circulation fans were on in all greenhouses.

When the large cooling system fans were on in the closed greenhouse, average b_5 to account for the additional infiltration was 0.23. The b_4 and b_7 values are from Okada and Takakura (1973).

7/ The b_9 value of 9 (volumes/hr)/(m/s) is from Maher and O'Flaherty (1973) using the data of Whittle and Lawrence (1960). The modeling data of Kozai and Sase (1978) are about three times larger than Whittle and Lawrence, but they did compute changes from ΔT. The b_{10} value of 4.5 comes from the Kozai and Sase data reduced by a factor of three.

8/ From the tomato data of B. A. Kimball, S. T. Mitchell, D. S. Jones, and G. Brooks, Evaluation of CO_2-enriched, unventilated, solar-heated greenhouses, 1979 Annual Report, U. S. Water Conservation Laboratory, Phoenix, AZ.

9/ Estimated by noting that the soil surface in U. S. Water Conservation Laboratory Greenhouse #2 appeared wet except for about 10 percent dry spots.

10/ The soil is a wet sand with an assumed thermal conductivity of 2 W/m·C and volumetric heat capacity of 2.5 MJ/m^3 · C (Kimball and Jackson, 1979). The depths Z_1, Z_2, Z_3 are taken to be at 4, 12, and 28 cm, respectively, and the bottom depth at 60 cm ($\Delta Z_1 = 4$, $\Delta Z_2 = 8$, $\Delta Z_3 = 16$, and $\Delta Z_4 = 32$ cm, respectively). A bottom depth of 60 cm is four times the diurnal damping depth, so diurnal storage is modeled, but not annual storage. The 24 C deep temperature is the annual average measured under U. S. Water Conservation Laboratory Greenhouse #2. This value of k_1 (Parameter 51) is based on the surface conductance for a smooth surface of 9.3 given by ASHRAE (1972, p. 357) and increased 20% to account for greater roughness. To satisfy the stability criteria (see "Integration of Differential" section), the minimum time stop allowed for a simulation is:

$$\Delta t < \frac{C_{A1}}{k_1 + k_2} = 0.2 \times 10^6/(11 + 25) = 5556 \text{ sec.} = 1.54 \text{ hr.}$$

11/ These test values are the initial soil temperatures for this example, and they correspond to a time of -1.0 hour (the size of the time step for this example). The final soil temperatures for this time step were 16.3505, 17.8276, and 18.9801. The temperatures for the next-to-last derivative iterations were 16.5098, 17.7198, and 18.9902 C.

Type 6 Fan or Pump (FAN)

PARAMETERS - 1
INPUTS - 4
OUTPUTS - 3
DERIVATIVES - 0

No.	Symbol	Item	Test Values
PARAMETERS:			
1.	M_{max}	Maximum flow rate (kg/s)	3.7
INPUTS:			
1.	T_i	Temperature of fluid flowing in (°C)	15.2124
2.	M_i	Flow rate flowing in. (For continuity only. This information is not used.)	0
3.	W_i	Humidity ratio of fluid flowing in	0.0111212
4.	γ	Control variable from 0.0 to 1.0	0.335500
OUTPUTS:			
1.	T_o	Temperature of fluid flowing out (is set equal to T_i)	15.2124
2.	M_o	Flow rate coming out (= γM_{max}) (kg/s)	1.24135
3.	W_o	Humidity ratio of fluid flowing out (is set equal to W_i.)	0.0111212

Type 7 Tee (TEE)

PARAMETERS - 1
INPUTS - 7
OUTPUTS - 6
DERIVATIVES - 0

No.	Item	Tee	Mixers: Known Inlets	Mixers: Known Outlets	Diverter	Test Values[1]
PARAMETERS:						
1.	Mode	1	2	3	4	3
INPUTS:						
1.	Temperature of stream 1	T_{i1}	T_{i1}	T_{i1}	T_{i1}	12.9
2.	Mass flow rate of stream 1 (for mode 3 inlet mixer, the flow rate of the outlet mixture must be known and supplied as an input)	m_{i1}	m_{i1}	m_o	m_{i1}	1.23632
3.	Humidity ratio of stream 1	W_{i1}	W_{i1}	W_{i1}	W_{i1}	0.00818
4.	Temperature of stream 2	T_{i2}	T_{i2}	T_{i2}	0	15.2124
5.	Mass flow rate of stream 2	m_{i2}	m_{i2}	0	0	0
6.	Humidity ratio of stream 2	W_{i2}	W_{i2}	W_{i2}	0	0.0111212
7.	Control variable (γ = 1 gives stream 1)	0	γ	γ	γ	0
OUTPUTS:						
1.	Temperature of outlet stream 1	T_{o1}	T_{o1}	T_{o1}	T_{o1}	15.2124
2.	Mass flow rate of output stream 1 (except mode 3)	m_{o1}	m_{o1}	m_{i1}	m_{o1}	0
3.	Humidity ratio of output stream 1	W_{o1}	W_{o1}	W_{o1}	W_{o1}	0.0111212
4.	Temperature of output stream 2	0	0	0	T_{o2}	0
5.	Mass flow rate of output stream 2 (except mode 3)	0	0	m_{i2}	m_{o2}	1.23632

No.	Item	Tee	Mixers Known Inlets	 Known Outlets	Diverter	Test Values[1/]
6.	Humidity ratio of output stream 2	0	0	0	W_{o2}	0

1/ The mode of 3 and an Input 2 of 1.23632 define a mixer whose outlet flow rate is 1.23632. A control variable of 0 (Input 7) switches the outlet temperature (Output 1) and humidity ratio (Output 3) to stream 2. See Unit 10 of the Solar Greenhouse System Example.

Type 8 Sensible Heat Exchanger (SXR)

PARAMETERS - 4
INPUTS - 5
OUTPUTS - 6
DERIVATIVES - 0

No.	Item	Mode				Test Values
PARAMETERS:		Parallel	Counter	Cross	Const. Eff.	
1.	Mode	1	2	3	4	3
2.	Overall heat transfer coefficient (W/C) or effectiveness for Mode 4	UA	UA	UA	E	1/5000
3.	Specific heat of hot side fluid (J/kg·C)	C_{ph}	C_{ph}	C_{ph}	C_{ph}	2/4190
4.	Specific heat of cold side fluid (J/kg·C)	C_{pc}	C_{pc}	C_{pc}	C_{pc}	3/1020
INPUTS:						
1.	Hot side inlet temperature (C)	T_{hi}	T_{hi}	T_{hi}	T_{hi}	16.9240
2.	Hot side mass flow rate (kg/s)	m_{hi}	m_{hi}	m_{hi}	m_{hi}	3.7
3.	Cold side inlet temperature (C)	T_{ci}	T_{ci}	T_{ci}	T_{ci}	15.0010
4.	Cold side mass flow rate (kg/s)	m_{ci}	m_{ci}	m_{ci}	m_{ci}	3.7
5.	Control variable to convert average to actual flow rates	γ	γ	γ	γ	1
OUTPUTS:						
1.	Hot side outlet temperature (C)	T_{ho}	T_{ho}	T_{ho}	T_{ho}	16.6067
2.	Hot side mass flow rate (kg/s) (is set = m_{hi})	m_{ho}	m_{ho}	m_{ho}	m_{ho}	3.7
3.	Cold side outlet temperature (C)	T_{co}	T_{co}	T_{co}	T_{co}	16.3043
4.	Cold side mass flow rate (kg/s) (is set = m_{ci})	m_{co}	m_{co}	m_{co}	m_{co}	3.7
5.	Total heat transfer rate (W)	Q_T	Q_T	Q_T	Q_T	4918.65

Type 8 Sensible Heat Exchanger (Cont'd)

No.	Item	Mode				Test Values
		Parallel	Counter	Cross	Eff.	
6.	Heat exchanger effectiveness	E	E	E	E	0.677754

1/ Representative of a coil that is 3.56 m long, 1.00 m high (24 tubes), and 1 tube row deep with 472 fins/m of tube and with water and air both flowing at 3.7 kg/s (crossflow), as extracted from the York Engineering Guide for Turbofin Water Coils (Borg-Warner Corp., 1971).

2/ Water

3/ Air

Type 9 Latent and Sensible Heat Exchanger (LXR)

PARAMETERS - 12
INPUTS - 8
OUTPUTS - 7
DERIVATIVES - 0

No.	Symbol	Item	Test Values[1]
PARAMETERS:			
1.		Mode	1
		1 = all direct contact	
		2 = direct contact only when interface below dew point	
2.		Liquid flow direction	-1
		1 = parallel flow	
		-1 = counter flow	
3.	A_{cs}	Cross sectional area (m^2)	4.6
4.	ℓ =	Length (m)	0.051
5.	c =	Heat capacity of liquid (J/kg · C)	4190
6.	C_1=	Coefficients for air side mass transfer coefficient	[2]37
7.	C_2=		[2]1.46
8.	C_3=	$K_D a_m = C_1 G_a^{C_2} G_L^{C_3}$: $K_D a_m$ in $\frac{kg}{s\ m^2} \cdot \frac{m^2}{m^3} = C_1 \left(\frac{kg}{s\ m^2}\right)^{C_2} \left(\frac{kg}{s\ m^2}\right)^{C_3}$	[2]0.10
9.	C_4=	coefficients for liquid side heat transfer coefficient	[2]65000
10.	C_5=		[2]0.4
11.	C_6=	$h_L a_H = C_4 G_a^{C_5} G_H^{C_6}$: $h_L a_H$ in $\frac{J}{s\ m^2 C} \cdot \frac{m^2}{m^3} = C_4 \left(\frac{kg}{s\ m^2}\right)^{C_5} \left(\frac{kg}{s\ m^2}\right)^{C_6}$	[2]0.83
12.	R_m=	Metal or structure resistance of indirect heat exchanger (s m^3C/J). If exchanger normally wet, add condensate resistance to R_m. Otherwise, condensate resistance assumed = 0.	0
INPUTS:			
1.	T_{a_1}	Air temp in (C)	15.2124

Type 9 Latent and Sensible Heat Exchanger (Contd)

No.	Symbol	Item	Test Values[1]
2.	F_{a_1}	Air mass flow rate (kg/s)	1.24135
3.	W_{a_1}	Air humidity ratio in (kg H_2O/kg air)	0.0111212
4.	T_{L_1}	Liquid temp in (°C)	18.4780
5.	F_{L_1}	Liquid flow rate (kg/s)	1.24135
6.	P	Barometric pressure (kPa)	97.91
7.	$T_{L_{2i}}$	Initial guess of the exit water temp. (Note: can connect to output (4) of this routine so values used will be the last ones computed.)	18.1788
8.	γ	The F_{a_1} and F_{L_1} are the average flow rates for a simulation time increment. Thus, γ is the control variable needed to get actual flow rates through the exchanger for the fraction of time it is in operation. The outputs are scaled to the averages.	0.335500
OUTPUTS:			
1.	T_{a_2}	Air temp out (°C)	15.6681
2.	F_{a_2}	Air flow rate (Is set = F_{a_1})	1.24135
3.	W_{a_2}	Air humidity ratio out (kg H_2O/kg air)	0.0114875
4.	T_{L_2}	Liquid temp out (°C)	18.1519
5.	F_{L_2}	Liquid flow rate (Is set = F_{L_1})	1.24135
6.	Q	Rate of total energy transfer from water to air (+) or air to water (-) (J/s)	5054.64
7.	E	Rate of evaporation (+) or condensation (-) of water (kg/s)	0.00135533

1/ See Time 0 of the Solar Greenhouse System Example. These values are for heating very humid greenhouse air at night with a direct contact mode of operation, and the program warns that possible fog conditions exist.

2/ From Kimball et al. (1977) for aspen excelsior pads.

Type 10 Solar Collector (CLECR)

PARAMETERS - 12
INPUTS - 8
OUTPUTS - 5
DERIVATIVES - 0

No.	Item	Mode				Test Values[1/]
PARAMETERS:						
1.	Mode	1	2	3	4	1
2.	Area (m^2)	A	A	A	A	15
3.	Geometry factor	F'	F'	F'	F'	[2/]1.0
4.	Heat capacity (J/kg · C)	C_p	C_p	C_p	C_p	4190
5.	Absorptance	α	α	α	α	[2/]0.91
6.	Transmittance	τ	τ	0	0	[2/]0.92
7.	Loss coefficient (W/m^2 · C)	U_L	0.	U_L	0.	[3/]15
8.	No. of panes	0.	N	N	N	0
9.	Emittance of plate	0.	E_p	0.	E_p	0
10.	Bottom and edge loss coefficient (W/m^2 · C)	0.	U_{be}	0.	U_{be}	0
11.	Tilt from horizontal (degree)	0.	S	0.	S	0
12.	Extinction coefficient x thickness	0.	0.	KL	KL	0
INPUTS:						
1.	Inlet temperature (°C)	T_i	T_i	T_i	T_i	16.5
2.	Mass flow rate (kg/s)	m	m	m	m	0.37
3.	Air temp (°C)	T_a	T_a	T_a	T_a	13.5
4.	Total solar radiation on tilted collector surface (W/m^2)	H_t	H_t	H_t	H_t	952

No.	Item	Mode				Test Values[1]
5.	Diffuse solar radiation on tilted collector surface (W/m^2)	0.	0.	H_D	H_D	77
6.	Windspeed (m/s)	0.	W	0.	W	2.76
7.	Angle of incidence (degree) of beam radiation	0.	0.	θ	θ	14
8.	Control variable to convert average to actual flow rate	γ	γ	γ	γ	1

OUTPUTS:

No.	Symbol	Item	Test Values
1.	T_O	Outlet temperature (°C)	23.2736
2.	m	Mass flow rate (kg/s) (Is set = inlet value)	0.37
3.	Q	Rate of energy collection (W)	10500
4.	U_L	Loss coefficient ($W/m^2 \cdot C$)	15
5.	$\tau\alpha$	Transmittance - adsorptance product	0.8372

---

[1] The parameters define a solar collector of the Rutgers Type (Mears, et al., 1977) which consists of a black sheet of polyethylene with shade cloth absorber and has an inflated tube made of clear polyethylene above and below for insulation.

[2] Chosen to give a $\tau\alpha$ product close to the 0.84 efficiency factor reported by Mears et al. (1977).

[3] Reported by Mears et al. (1977).

Type 11 Stratified Fluid Tank with Internal Heater (TANK)

PARAMETERS - 12
INPUTS - 6
OUTPUTS - 8
DERIVATIVES - UP to 10

No.	Symbol	Item	Values[1/]
PARAMETERS:			
1.	N	Number of sections (= No. of derivatives)	1
2.	V	Volume (m^3)	63
3.	H	Height of tank (m)	1.5
4.	C_{pf}	Specific heat of fluid (J/kg)	4190
5.	ρ_f	Density of fluid (kg/m^3)	1000
6.	U	Heat loss coefficient ($W/m^2 \cdot C$)	0.1
7.	T_o	Initial average tank temp (C)	18.5
8.	Q_{HE}	Max. capacity of internal resistance heater (W). (Set = 0 if not using heater.)	0
9.	ℓ	Number of section from top where heater is located	1
10.	ℓ_T	Number of section from top where internal thermostat is located	1
11.	T_{set}	Internal thermostat setting (C)	0
12.	η	Flag to indicate whether external control variable is to be used. (1 = yes, 0 = no)	0
INPUTS:			
1.	T_{in}	Temperature from heat source (C)	18.1519
2.	m_h	Flow rate from heat source (kg/s)	1.24135

Type 11 Stratified Fluid Tank with Internal Heater (Cont'd)

No.	Symbol	Item	Values[1/]
3.	T_L	Cold temperature coming from load (C)	18.4780
4.	m_L	Flow rate from load (kg/s)	0
5.	T_{env}	Temperature of environment (C)	12.9
6.	γ_{HE}	External control variable (0 if PARI(12) = 0). Vary from 0 to 1 to vary heater output from 0 to Q_{HE}.	0
OUTPUTS:			
1.	T_N	Temp to heat source from bottom of tank (C)	18.4780
2.	m_h	Flow rate to heat source (kg/s)	1.24135
3.	T_1	Temp to load from top of tank (C)	18.4780
4.	m_L	Flow rate to load (kg/s)	0
5.	Q_{env}	Heat loss to environment (W)	66.0770
6.	Q_{tank}	Heat delivered from tank to load (W)	0
7.	ΔE	Change in stored heat since initial time (J)	5.81321E6
8.	Q_I	Heat delivered to tank from heater (W)	0
DERIVATIVES (INITIAL VALUES OF DEPENDENT VARIABLES):[2/]			
1.		Temperature of top tank section (C)	18.5
2.		Temperature at second tank section (C)	-
.			
.			
.			
N.		Temperature of bottom tank section (C)	-

[1/] See time 0.0 for Solar Greenhouse System Example.

[2/] This test value of 18.5C is the initial tank water temperature for this example, which corresponds to a time of -1.0 hours (the size of the time step for this example). The final tank temperature for this example was 18.4780C, and for the next-to-last derivative iteration it was also 18.5.

Type 12 Time Dependent Forcing Function (TIMFN)

PARAMETERS - UP TO 99
INPUTS - 0
OUTPUTS - 2
DERIVATIVES - 0

No.	Symbol	Item	Test Values 1/
PARAMETERS:			
1.	N_P	The total number of parameters, 2N+3, where N is one less than the total number of defining points	13
2.	t_0	Time of first given point (elapsed time in hr after start of simulation)	0
3.	F_0	Function value of first given point	0.0
4.	t_1	Time of second given point (hr)	6
5.	F_1	Function value of second given point	0.0
6.	t_2	Time of third point	6
7.	F_2	Function value of third point	1.0
8.	t_3	Time of fourth point	18
9.	F_3	Function value of fourth point	1.0
10.	t_4	Time of fifth point	18
11.	F_4	Function value of fifth point	0.0
.	.		
.	.		
.	.		
2N+2.	t_N	Time of end of cycle = time of last given point (hr)	24
2N+3.	F_N	Function value of last given point	0.0
OUTPUTS:			
1.	F	The function value at the present value of TIME	0
2.	(1. - F)		1

1/ This set of parameters produces a "0" for Output 1 from 0 to 6 and 18 to 24 hours from the start of the simulation and a "1" from 6 to 18 hours.

Type 13 Infinite Volume Storage Reservoir (RSVOR)

PARAMETERS - 1 more than number of outputs
INPUTS - 0
OUTPUTS - up to 80
DERIVATIVES - 0

No.	Symbol	Item	Test Values
PARAMETERS:			
1.	N_p	Total number of parameters	4
2.	P_1		0.0
3.	P_2		0.8
.			
.			
.			
N_p.	P_{p-1}		0.2
OUTPUTS:			
1.		The value of P_1	0.0
2.		The value of P_2	0.8
.		. . .	
.		. . .	
.		. . .	
N_{p-1}		. . . P_{p-1}	0.2

Type 14 Complicated Greenhouse (CGH)

PARAMETERS - 76
INPUTS - 21 + 3 * No. of external devices
OUTPUTS - 46 + 3 * No. of external devices
DERIVATIVES - 0

No.	Math Symbol	Program Symbol	Item	Test Values[1/]
PARAMETERS:				
1.	J	JMAX	No. of external devices which add (or remove) sensible and/or latent heat from greenhouse air	2
2.	A_c	AC	Area of cover (m^2)	62
3.	A_g	AG	Area of soil (m^2)	27
4.	v_{ai}	VAI	Volume of air in greenhouse (m^3)	73
5.	ℓ	LNV	Length of row of vegetation (m)	5.0
6.	s	RSV	Row spacing (must not = 0) (m)	1.0
7.	N_e	NE	Number of vegetation rows per individual curtain heat exchanger (must not = 0. Set equal to 1.0 if not using exchanger).	1
8.	x_e	HTE	Maximum height of curtain heat exchanger	0
9.	ρ_v	RHOV	Reflectance of vegetation for solar radiation	0.13
10.	ρ_g	RHOG	Reflectance of soil for solar radiation	0.16
11.	ε_v	EPV	Emittance of vegetation for thermal radiation	0.98
12.	ε_g	EPG	Emittance of soil for thermal radiation	0.95
13.	ε_e	EPED	Emittance of dry curtain heat exchanger for thermal radiation	0
14.	c_{xc}	CXC	Heat capacity of fluid that carries energy to cover (J/kg · C)	0
15.	c_{xg}	CXG	Heat capacity of fluid that carries energy to soil storage layer (J/kg · C)	0

No.	Math Symbol	Program Symbol	Item	Test Values[1]
16.	c_{xe}	CXE	Heat capacity of fluid that carries energy to curtain heat exchanger (J/kg · C)	0
17.	b_1	B(1)	Constants in equation for outside transfer coefficient $h_o = b_1 + b_2 u_{ao}$	5.7
18.	b_2	B(2)	(h_o in $W/m^2 \cdot C$, u_{ao} in m/s)	3.8
19.	b_3	B(3)	Constants in equation for inside transfer coefficient from temp. diff. $h_i = b_3(\Delta T)^{b_4}$	1.5
20.	b_4	B(4)	(h_i in $W/m^2 \cdot C$, T in C)	0.33
21.	b_5	B(5)	Constants in equation for natural	9.0
22.	b_6	B(6)	ventilation through ventilators (when $\gamma_N = 1$)	4.5
23.	b_7	B(7)	$u_N = (b_5 u_{ao} + b_6 \sqrt{T_{ai} - T_{ao}} + b_7)\ \gamma_N$ (u_N in volumes/hr, u_{ao} in m/s, T_{ai} and T_{ao} in C)	0
24.	b_8	B(8)	Coefficients in equation for leaf stomatal resistance. b_8 and b_{10} must not equal zero.	100
25.	b_9	B(9)	$r_v = b_8 + b_9/(S_o \tau_S + b_{10})$	20300
26.	b_{10}	B(10)	(r_v in $m^2 s/kg$, S_o in W/m^2)	17
27.	r_g	RSOIL	Soil surface resistance to evaporation (0 for wet surface, 10000. for dry) ($m^2 s/kg$)	100
28.	h_{p1}	HPOWR	Inside heat transfer coefficient when power circulation fan is on ($\gamma_p = 1$) ($W/m^2 \cdot C$)	6
29.	X_{RM}	XRM	Maximum rated output capacity of infrared heater (W)	0
30.	f	FR	Fraction of energy from infrared heater that is radiant	0

Type 14 Complicated Greenhouse (Cont'd)

No.	Math Symbol	Program Symbol	Item	γ_f	γ_{co}	γ_{ci}	Test Values[1/]

Parameters 31 through 76 must correspond to particular values of the control variables for fluid flow, γ_f; outer cover, γ_{co}; inner cover, γ_{ci}; and powered circulation, γ_p.

No.	Math Symbol	Program Symbol	Item	γ_f	γ_{co}	γ_{ci}	Test Values[1/]
31.	τ_{Sco0}	TAUSO	Transmittance of outer cover for solar radiation	–	0	–	0.66
32.	τ_{Sco1}			–	1	–	0
33.	τ_{Sci00}	TAUSI	Transmittance of inner cover for solar radiation	0	–	0	1.00
34.	τ_{Sci01}			0	–	1	0
35.	τ_{Sci10}			1	–	0	0
36.	τ_{Sci11}			1	–	1	0
37.	α_{Sco0}	ALSO	Absorptance of outer cover for solar radiation	–	0	–	0.24
38.	α_{Sco1}			–	1	0	0
39.	α_{Sci00}	ALSI	Absorptance of inner cover for solar radiation	0	–	0	0.00
40.	α_{Sci01}			0	–	1	0
41.	α_{Sci10}			1	–	0	0
42.	α_{Sci11}			1	–	1	0
43.	U_{c00}	UC	Thermal conductance of space between covers (W/m^2 · C)	0	–	0	160
44.	U_{c01}			0	–	1	0
45.	U_{c10}			1	–	0	0
46.	U_{c11}			1	–	1	0
47.	τ_{Rco0}	TOO	Transmittance of dry outer cover for thermal radiation	–	0	–	0.07
48.	τ_{Rco1}			–	1	–	0
49.	τ_{Rci00}	TOI	Transmittance of dry inner cover for thermal radiation	0	–	0	1.00
50.	τ_{Rci01}			0	–	1	0
51.	τ_{Rci10}			1	–	0	0

No.	Math Symbol	Program Symbol	Item				Test Values[1]
				γ_f	γ_{co}	γ_{ci}	
52.	τ_{Rci11}			1	-	1	0
53.	ε_{coo0}	ECOOD	Emittance of outer side of outer cover for thermal radiation	-	0	-	0.87
54.	ε_{coo1}			-	1	-	0
55.	ε_{coi0}	ECOID	Emittance of inner side of outer cover for thermal radiation	-	0	-	0.87
56.	ε_{coi1}			-	1	-	0
57.	ε_{cio00}			0	-	0	0.00
58.	ε_{cio01}	ECIOD	Emittance of outer side of inner cover for thermal radiation	0	-	1	0
59.	ε_{cio10}			1	-	0	0
60.	ε_{cio11}			1	-	1	0
61.	ε_{cii00}			0	-	0	0.00
62.	ε_{cii01}	ECIID	Emittance of inner side of inner cover for thermal radiation	0	-	1	0
63.	ε_{cii10}			1	-	0	0
64.	ε_{cii11}			1	-	1	0
					γ_{ci}	γ_p	
65.	b_{1100}				0	0	0.12
66.	b_{1101}	B(11)			0	1	0.12
67.	b_{1110}				1	0	0
68.	b_{1111}		Coefficients for infiltration Equation 14-111 for velocity of air passing through cover		1	1	0
69.	b_{1200}				0	0	0.039
70.	b_{1201}	B(12)			0	1	0.039
71.	b_{1210}		$u_{cI} = b_{11}u_{ao}+b_{12}\sqrt{T^o_{ai}-T_{ao}} + b_{13}$ (u_{cI} in mm/s, u_{ao} in m/s and T^o_{ai} and T_{ao} in C)		1	0	0
72.	b_{1211}				1	1	0

Type 14 Complicated Greenhouse (Cont'd)

No.	Math Symbol	Program Symbol	Item			Test Values[1/]
				γ_{ci}	γ_p	
73.	b_{1300}	B(13)		0	0	0.0
74.	b_{1301}	B(13)		0	1	0.23
75.	b_{1310}	B(13)		1	0	0
76.	b_{1311}	B(13)		1	1	0

INPUTS:

No.	Math Symbol	Program Symbol	Item	Test Values
1.	S_o	ST	Total downcoming solar radiation outside (W/m^2 of land area)	0.0
2.	R_{ao}	RA	Sky thermal radiation (W/m^2 of land area)	319
3.	u_{ao}	UAO	Outside windspeed (m/s)	2.51
4.	P_{ao}	PAO	Outside barometric pressure (kPa)	97.91
5.	T_{ao}	TAO	Outside air temperature (C)	12.9
6.	W_{ao}	WAO	Outside humidity ratio (kg/kg)	0.00818
7.	y	HTV	Height of row of vegetation (m); set = 0 for no veg	0.8
8.	w	WDV	Width of row of vegetation (m) (0 to r_{sv})	0.2
9.	γ_f	GAM(1)	Control variable for fluid flow in cover (0 for no flow to 1 for maximum flow)	0
10.	γ_{co}	GAM(2)	Control variable for outer cover properties (0 to 1)	0
11.	γ_{ci}	GAM(3)	Control variable for inner cover properties properties (0 to 1)	0
12.	γ_p	GAM(4)	Control variable for powered air circulation	1
13.	γ_N	GAM(5)	Control variable for natural ventilation (0 for shut to 1 for max open)	0
14.	γ_e	GAM(6)	Control variable for curtain heat exchanger	0

No.	Math Symbol	Program Symbol	Item	Test Values1/
15.	γ_R	GAM(7)	Control variable for infrared heater	0
16.	T_{xc}	TXC	Temperature of fluid from external device going to cover (C)	0
17.	M_{xc}	MXC	Mass flow rate of fluid from external device going to cover (kg/s)	0
18.	T_{xg}	TXG	Temperature of fluid from external device going to soil storage (C)	0
19.	M_{xg}	MXG	Mass flow rate of fluid from external device going to soil storage (kg/s)	0
20.	T_{xe}	TXE	Temperature of fluid from external device going to curtain heat exchanger (C)	0
21.	M_{xe}	MXE	Mass flow rate of fluid from external device going to curtain heat exchanger (kg/s)	0
22.	T_{x1}	TX(1)	Temperature from external device 1 (C)	15.2708
23.	M_{x1}	MX(1)	Mass flow rate from external device 1 (kg/s)	0
24.	W_{x1}	WX(1)	Humidity ratio from external device 1 (kg/kg)	0.0111667
25.	T_{x2}	TX(2)	Temperature from external device 2 (C)	15.7195
26.	M_{x2}	MX(2)	Mass flow from external device 2 (kg/s)	1.23632
27.	W_{x2}	WX(2)	Humidity ratio from external device 2 (kg/kg)	0.0115277
etc.	etc.	etc.	etc.	
OUTPUTS:				
1.	T_{co}	GH(1)	Outer cover temperature (C)	12.8986
2.	T_{ci}	GH(2)	Inner cover temperature (C)	13.1032
3.	T_v	GH(3)	Vegetation temperature (C)	15.0948
4.	T_{go}	GH(4)	Soil surface temperature (C)	16.9943
5.	T_e	GH(5)	Curtain heat exchanger temperature (C)	-3.7584
6.	T_{ai}	GH(6)	Greenhouse air temperature (C)	15.2124

Type 14 Complicated Greenhouse (Cont'd)

No.	Math Symbol	Program Symbol	Item	Test Values[1/]
7.	W_{ai}	GH(7)	Greenhouse air humidity ratio (kg/kg)	0.0111212
8.	T_{gs}	GH(8)	Soil storage temperature (C)	21.1545
9.	S_{co}	SCO	Solar radiation absorbed by outer cover (W)	0
10.	S_{ci}	SCI	Solar radiation absorbed by inner cover (W)	0
11.	S_{v}	SV	Solar radiation absorbed by vegetation (W)	0
12.	S_{g}	SG	Solar radiation absorbed by soil (W)	0
13.	R_{con}	OUTI(13)	Net thermal radiation for outer cover (W)	-2030.93
14.	R_{cin}	OUTI(14)	Net thermal radiation for inner cover (W)	0
15.	R_{vn}	OUTI(15)	Net thermal radiation for vegetation (W)	-59.8733
16.	R_{gn}	OUTI(16)	Net thermal radiation for soil (W)	-354.716
17.	R_{en}	OUTI(17)	Net thermal radiation for curtain heat exchanger (W)	-12.5058
18.	C_{coH}	OUTI(18)	Sensible heat convected from outer cover (W)	-1.3173
19.	C_{coE}	OUTI(19)	Latent heat convected from outer cover (W)	0
20.	C_{ciH}	OUTI(20)	Sensible heat convected to inner cover (W)	784.607
21.	C_{ciE}	OUTI(21)	Latent heat convected to inner cover (W)	1245.00
22.	C_{vH}	OUTI(22)	Sensible heat convected from vegetation (W)	-38.0849
23.	C_{vE}	OUTI(23)	Latent heat convected from vegetation (W)	-21.7827
24.	C_{gH}	OUTI(24)	Sensible heat convected from soil (W)	288.666
25.	C_{gE}	OUTI(25)	Latent heat convected from soil (W)	351.514
26.	C_{eH}	OUTI(26)	Sensible heat convected from curtain heat exchanger (W)	-6.1465

No.	Math Symbol	Program Symbol	Item	Test Values[1/]
27.	C_{eE}	OUTI(27)	Latent heat convected from curtain heat exchanger (W)	-6.3593
28.	I_H	OUTI(28)	Sensible heat lost by infiltration (W)	103.132
29.	I_E	OUTI(29)	Latent heat lost by infiltration (W)	316.904
30.	N_H	OUTI(30)	Sensible heat lost by natural ventilation (W)	0
31.	N_E	OUTI(31)	Latent heat lost by natural ventilation (W)	0
32.	G_c	GC	Conduction from inner to outer cover (W)	2029.63
33.	G_0	OUTI(33)	Surface soil heat flux (W)	-994.902
34.	G_{s0}	OUTI(34)	Soil heat flux leaving bottom of upper layer (W)	62.5664
35.	G_{sd}	OUTI(35)	Soil heat flux entering top of bottom semi-infinite region (W)	62.5742
36.	U	OUTI(36)	Overall coefficient of heat transmission including thermal IR ($W/m^2 \cdot C$)	20.0654
37.	X_c	OUTI(37)	Sensible heat added to cover from external device (W)	0
38.	--	OUTI(38)	Cover fluid exit temperature (C)	26.2064
39.	M_{xc}	OUTI(39)	Mass flow rate of cover fluid (kg/s)	0
40.	X_g	OUTI(40)	Sensible heat added to soil storage from external device (W)	0
41.	--	OUTI(41)	Soil storage fluid exit temperature (C)	42.3089
42.	M_{xg}	OUTI(42)	Mass flow rate of fluid from storage (kg/s)	0
43.	X_e	OUTI(43)	Sensible heat added to the curtain heat exchanger from external device (W)	0
44.	--	OUTI(44)	Curtain heat exchanger fluid exit temperature(C)	-7.5168

Type 14 Complicated Greenhouse (Cont'd)

No.	Math Symbol	Program Symbol	Item	Test Values[1/]
45.	M_{xe}	OUTI(45)	Mass flow rate of fluid from curtain heat exchanger (kg/s)	0
46.	X_R	XR	Energy output from the infrared heater (W)	0
47.	X_{H1}	OUTI(47)	Sensible heat added by external device 1 (W)	0
48.	M_{X1}	MX(1)	Flow rate of external device 1 (kg/k)	0
49.	X_{E1}	OUTI(49)	Latent heat added by external device 1 (W)	0
50.	X_{H2}	OUTI(50)	Sensible heat added by external device 2 (W)	643.273
51.	M_{X2}	MX(2)	Flow rate of exteraal device 2 (kg/s)	1.23632
52.	X_{E2}	OUTI(52)	Latent heat added by external device 2 (W)	1238.54
etc.	etc.	etc.	etc.	

ADDITIONAL INFORMATION FOR SOIL CONDUCTION TRANSFER FUNCTIONS:

	Math Symbol	Program Symbol	Item	Test Values
	M	MMAX	Maximum number of conduction transfer functions	11
	G_{0,t_o-1}	GSOLD(1)	Soil heat flux at top of soil for previous step (W, positive downward)	-500
	G_{S0,t_o-1}	GSOLD(2)	Soil heat flux at top of semi-infinite region for previous time step (W, positive downward)	-500
	B_r	BR	Common ratio	0.72749
	T_d	TD	Temperature at great depth in the soil (C)	18
	B_{41}	BRF(4,1)	First thermal response factor for semi-infinite region	17.34
	m	I	Index for previous time steps	1
	B_{1m}	BRF(1,I)	Conduction transfer functions	39.3336
	B_{2m}	BRF(2,I)	Conduction transfer functions	0.0018
	B_{3m}	BRF(3,I)	Conduction transfer functions	46.6613

No.	Math Symbol	Program Symbol	Item	Test Values[1/]
	$T_{go,t_o-(m+1)\delta}$	TGOLD(I)	Soil surface temperature at the t_o-m+1 time step (C) (omit for m = 1)	-
	$T_{gS,t_o-(m+1)\delta}$	TGSOLD(I)	Soil temperature at top of semi-infinite region for the t_o-m+1 time step (C) (omit for m = 1)	-
			repeat for all m	

1/ Data were from 0600, 11 December 1978, at Phoenix, Arizona. The parameters define a small fiberglass greenhouse with tomatoes for the crop. The "soil" is 30 cm of sand overlying loam (Kimball 1983). The greenhouse is a component of solar greenhouse system as illustrated in figure 28 and discussed in the "Example" section. See table 1 for an explanation of parameter choices.

2/ The initial or "old" values of T_{co}, T_{ci}, T_v, T_g, T_e, T_{ai}, W_{ai}, and T_{gs} were 12.9268, 13.1346, 15.1485, 17.0116, -3.68257, 15.2708, 0.0111667, and 21.1545, respectively.

Type 15 Simple Greenhouse (SGH)

PARAMETERS - 18
INPUTS - 8 + 2* No. of external devices
OUTPUTS - 6
DERIVATIVES - 0

No.	Math Symbol	Program Symbol	Item	Test Values[1/]
PARAMETERS:				
1.	J	JMAX	Number of external devices which contribute enthalpy	1
2.	A_c	AC	Area of cover (m^2)	62
3.	A_g	AG	Area of soil (m^2)	27
4.	v_{ai}	VAI	Volume of air inside (m^3)	73
5.	f_λ	FL	Fraction of ventilation heat removal that is latent (0 to almost 1. Must not = 1)	0.5
for $\gamma_N = 0$:				
6.	b_2	B2	Coefficients in equation for natural	[2/]0.23
7.	b_3	B3	ventilation $u_N = b_2 + b_3\ u_{ao}$ u_N in air changes per hour and u_{ao} in m/s	[2/]0.08
for $\gamma_N = 1$:				
8.	b_2	B2	"	[2/]0.0
9.	b_3	B3		[2/]9.0
10.	u_{Max}	ARMAX	Maximum air changes per hour with fan ventilation	156
11.	η	ETA	Saturation efficiency of evaporative cooler (fraction)	0.75
12.	ρ_{vg}	RHOV	Average reflectance of crop and soil for solar radiation	[3/]0.14
for $\gamma_c = 0$:				
13.	τ_s	TAUS	Transmittance of cover for solar radiation	[3/]0.66

Type 15 Simple Greenhouse (Cont'd)

No.	Math Symbol	Program Symbol	Item	Test Values[1/]
14.	b_0	BO	Coefficients in equation for U	[4/]8.8
15.	b_1	B1	$U = b_0 + b_1 u_{ao}$ (U in $W/m^2 \cdot C$ and u_{ao} in m/s)	[4/]1.6
for $\gamma_c = 1$:				
16.	τ_S	TAUS	Transmissivity of cover	[3/]0.66
17.	b_0	BO	Coefficients in equation for U	[4/]8.8
18.	b_1	B1		[4/]1.6
INPUTS:				
1.	S_o	ST	Total downcoming solar radiation (W/m^2 of land area)	0
2.	u_{ao}	UAO	Outside windspeed (m/s)	2.51
3.	P_{ao}	PAO	Barometric pressure (kPa)	97.91
4.	T_{ao}	TAO	Outside dry bulb (C)	12.9
5.	T_{wb}	TWBO	Outside wet bulb (C)	11.5
6.	γ_c	GAMC	Control variable for cover properties (0 to 1) $P = P_0(1 - \gamma_c) + P_1(\gamma_c)$	0
7.	γ_p	GAMP	Control variable for powered ventilation. 0 for fans off, 1 for fans on	0
8.	γ_N	GAMN	Control variable for natural ventilation. 0 for shut, 1 for maximum open	0
9.	T_{x1}	XIN(9)	Temperature from external device 1 (C)	23.2892
10.	M_{x1}	XIN(10)	Mass flow rate from external device 1 (kg/s)	0.26
11.	T_{x2}	XIN(11)	Temperature from external device 2 (C)	-
12.	M_{x2}	XIN(12)	Mass flow rate from external device 2 (kg/s)	-
etc.	etc.	etc.	etc.	

Type 15 Simple Greenhouse (Cont'd)

No.	Math Symbol	Program Symbol	Item	Test Values[1]
OUTPUTS:				
1.	T_{ai}	TAI	Greenhouse temperature (C)	15.4280
2.	S_i	SI	Solar radiation absorbed in greenhouse (W)	0
3.	$\sum_j X_j$	SUMX	Total external heat supplied to greenhouse (W)	2084.78
4.	C	OUTI(4)	Conduction out through cover including IR (W)	2008.74
5.	-	OUTI(5)	Sensible heat removed by ventilation (W)	38.02
6.	V	OUTI(6)	Total sensible plus latent heat removed by ventilation (W)	76.04

1/ Data were from 00:00, 7 March 1978, at Phoenix, Arizona. The parameters define a small conventional fiberglass greenhouse, as discussed in the Example" section and illustrated in figure 17.

2/ From Whittle and Lawrence (1960)

3/ Measured in USWCL Greenhouse Number 2

4/ Measured in USWCL Greenhouse Number 2. Corresponding values suggested by American Society of Agricultural Engineers EP406 (1982) are 8.3 and 0.0 for a fiberglass greenhouse 3 m in height and with an infiltration rate of one air change per hour.

Type 16 Heater (HEATR)

PARAMETERS - 3
INPUTS - 4
OUTPUTS - 3
DERIVATIVES - 0

No.	Symbol	Item	Test Values[1/]
PARAMETERS:			
1.	H_{max}	Maximum total heating capacity of heater (W)	6850
2.	M_{max}	Maximum mass flow rate of internal fan of heater (kg/s)	0.26
3.	E_{max}	Maximum rate of water vapor addition (kg/s)	0.0
INPUTS:			
1.	T_{ai}	Temperature of air entering (°C)	15.4280
2.	M_{ai}	Mass flow rate of air entering (for continuity only)	0
3.	W_{ai}	Humidity ratio of air entering (kg/kg)	0
4.	γ	Control variable	0.301498
OUTPUTS:			
1.	T_{a2}	Temperature of exit air (°C)	23.3318
2.	M_{a2}	Mass flow rate of air (kg/s)	0.26
3.	W_{a2}	Humidity ratio of exit air (kg/kg)	0

[1/] From Time 0 of Simple Greenhouse Example

Type 17 Night Sky Radiator with Insulating Air Layer (NSRAD)

PARAMETERS - 17
INPUTS - 9
OUTPUTS - 8
DERIVATIVES - 0

No.	Symbol	Item	Test Values[1/]
PARAMETERS:			
1.	L	Length of radiator (m)	15
2.	W	Width of radiator (m)	2
3.	b_0	Constants in equation for outside convection heat transfer coefficient. $h_o = b_0 + b_1 u_a$ where h_o in $W/m^2 \cdot C$ and u_a in m/s.	[2/]5.7
4.	b_1		[2/]3.8
5.	b_2	Constants in equation for inside transfer coefficient $h_1 = b_2(\Delta T)^{b_3}$ where h_1 is $W/m^2 \cdot C$ and ΔT in ^oC.	[3/]1.5
6.	b_3		[3/]0.33
7.	b_4	Constant in equation for water transfer coefficient $h_\ell (W/m^oC) = b_4 \ (\Delta T)^{0.33}$	[4/]230
8.	τ_{cw}	Transmittance of cover for thermal radiation in 8-14μm atmospheric window (unused when mode = 2 or 3)	[5/]0.85
9.	τ_{co}	Transmittance of cover outside window (unused when mode = 2 or 3)	[5/]0.80
10.	ρ_{cw}	Reflectance of cover in window (unused when mode = 2 or 3)	[6/]0.08
11.	ρ_{co}	Reflectance of cover outside window (unused when mode = 2 or 3)	[6/]0.08
12.	ε_{sw}	Emittance of surface in window (unused when mode = 3)	[7/]0.92
13.	ε_{so}	Emittance of surface outside window (unused when mode = 3)	[7/]0.05

No.	Symbol	Item	Test Values[1/]
14.	M	Mode: Set = 1 for case of transparent cover over insulating air layer Set = 2 for case of no insulating air layer. Then program will set h_1 = 500 W/m^2 · C for "infinite convection between layers." Set = 3 case of water pond. W_{co}, the humidity ratio at cover surface will be set at saturation value, and τ_{co}, τ_{co} = 0 and ρ_{cw}, ρ_{co} = 0.04 for water. ε_{sw} and ε_{so} = 0.96, same as cover.	1
15.	η	Set = 1 to get segment-by-segment summary printed, otherwise 0.	0
16.	N	Total number of segments	1
17.	$(\tau\alpha)_S$	Effective transmittance-absorptance product for solar radiation	0.5
INPUTS:			
1.	$T_{\ell 1}$	Entering water temp (^{o}C)	24.999
2.	F	Water flow rate (kg/s)	0.154553
3.	R_a	Total long-wave sky radiation (W/m^2)	398
4.	R_{aw}	8-14μm sky radiation (W/m^2)	87
5.	S_a	Solar radiation impinging on radiator (W/m^2)	0
6.	u_a	Outside windspeed (m/s)	1.80
7.	P_{ao}	Barometric pressure (kPa)	97.19
8.	T_{ao}	Outside dry bulb temp (^{o}C)	29.9
9.	W_{ao}	Outside humidity ratio (kg/kg)	0.0102400
OUTPUTS:			
1.	$T_{\ell J}$	Exit water temp (C)	22.8452
2.	F	Water flow rate (= inlet flow rate (kg/s))	0.154553

Type 17 Night Sky Radiator with Insulating Air Layer (Cont'd)

No.	Symbol	Item	Test Values[1/]
3.	T_c	Average cover temperature (C)	29.2557
4.	T_s	Average surface temperature (C)	23.7772
5.	Q	Total rate of enthalpy change of the water (W)	-1394.75
6.	R_{nc}	Net radiation (W)	-1888.03
7.	H	Sensible heat (W)	242.369
8.	E	Latent heat (W)	0

1/ This example is for a radiator with high emittance in atmospheric window and low emittance outside the window. It is covered with polyethylene. The weather inputs are from 00:00, 25 August 1978, for Phoenix, Arizona.

2/ From the McAdam's expression (Duffie and Beckman, 1974, p. 83).

3/ From ASHRAE (1972, p. 40)

4/ From Duffie and Beckman's (1974, p. 81) Equation 4.11.8 for water with the transfer being to a single plate. The minimum value would be about 60 for thermal conduction across 1 cm of water.

5/ From Catalanotti et al. (1975, Fig. 5) for polyethylene

6/ Godbey et al. (1979) measured an average thermal transmittance value for polyethylene of 0.80, which basically agrees with Catalanotti et al.[5/] Bailey (1981), on the other hand, measured 0.85 for the average transmittance, but also he measured an average emittance of 0.12. Taking the values of Godbey et al. and Catalanotti et al. for transmittance and Bailey's value for the emittance yields 0.08 for the average reflectance, which should be relatively independent of wavelength (unlike emittance).

7/ From Harrison and Walton (1978) for white paint with a high TiO_2 content (although Michell and Biggs (1979) later showed that $\varepsilon_{so} = 0.82$ for TiO_2 paint).

Type 18 Evaporative Air Cooler (COOLR)

PARAMETERS - 2
INPUTS - 5
OUTPUTS - 4
DERIVATIVES - 0

No.	Symbol	Item	Test Values[1/]
PARAMETERS:			
1.	M_{max}	Maximum air mass flow rate (kg/s)	3.7
2.	η	Effectiveness or saturation efficiency (no units, is a fraction).	0.75
INPUTS:			
1.	T_{di}	Inlet dry bulb temperature (C)	18.8
2.	M_i	Inlet mass flow rate. Unused. For continuity only.	0.1976
3.	T_{wi}	Inlet wet bulb temperature (C)	13.4
4.	γ	Control variable	0.053144
5.	P	Barometric pressure (kPa)	98.20
OUTPUTS:			
1.	T_{do}	Outlet dry bulb (C)	14.75
2.	M_o	Outlet mass flow rate (kg/s)	0.196633
3.	W_o	Outlet humidity ratio (kg/kg)	0.0093255
4.	E	Evaporation rate (kg/s)	0.332733E-3

1/ Data were from 1200, 7 March 1978, at Phoenix, Arizona. The cooler was connected to a Type 5 Greenhouse.

Type 19 Rock Bed (ROCK)

PARAMETERS - 8
INPUTS - 10
OUTPUTS - 11 + No. of segments
DERIVATIVES - No. of segments

No.	Symbol	Item	Test Values[1/]
PARAMETERS:			
1.	N	Number of segments	5
2.	L	Length (height) of rock bed (m)	[1/] 2
3.	A	Cross-sectional area of rock bed (m^2)	[1/] 40
4.	s	Length of perimeter around rock bed (m)	[1/] 32
5.	D_r	Equivalent diameter of individual rocks (m)	[1/] 0.019
6.	c_{rv}	Effective volumetric heat capacity of rocks including void space ($J/m^3 \cdot C$)	[1/] 4.7E5
7.	U	Loss coefficient ($W/m^2 \cdot C$)	[1/] 0.4
8.	κ	Effective axial thermal conductivity ($W/m \cdot C$)	[2/] 0.3
INPUTS:			
1.	T_{a1}	Temperature of air entering top (C)	15.2209
2.	F_t	Mass flow rate entering top (kg/s)	0
3.	W_{a1}	Humidity ratio of air entering top (kg/kg)	0.00672648
4.	$T_{a(N+1)}$	Temperature of air entering bottom (C)	15.2209
5.	F_b	Mass flow rate entering bottom (kg/s)	1.61114
6.	$W_{a(N+1)}$	Humidity ratio of air entering bottom (kg/kg)	0.00672648
7.	γ_t	The F_t and F_b are the average flow rate for a simulation time. These γ's are the air flow	0
8.	γ_b	rate control variables needed to get actual flow rates through the rock bed for the fraction of time it is in operation. Then the exit temperature and humidity ratios are scaled to the average flow rates.	0.947728
9.	P	Barometric pressure (kPa)	97.40

Type 19 Rock Bed (Cont'd)

No.	Symbol	Item	Test Values[1/]
10.	T_e	Temperature of environment surrounding rock bed (C)	4.2
OUTPUTS:			
1.	$T_{a(N+1)}$	Temperature of air leaving bottom (C)	15.2209
2.	F_t	Mass flow rate of air entering top and leaving bottom (kg/s)	0
3.	$W_{a(N+1)}$	Humidity ratio of air leaving bottom (kg/kg)	0.00672648
4.	T_{a1}	Temperature of air leaving top (C)	19.5766
5.	F_b	Mass flow rate of air entering bottom and leaving top (kg/s)	1.61114
6.	W_{a1}	Humidity ratio of air leaving top (kg/kg)	0.00672648
7.	Q_t	Total rate of energy addition to bed by stream entering top (W)	0
8.	E_t	Rate of water condensation from stream entering top (kg/s)	0
9.	Q_b	Total rate of energy addition to bed by stream entering bottom (kg/s)	-7740.47
10.	E_b	Rate of water condensation from stream entering bottom (kg/s)	-.90E-8
11.	Q_{env}	Heat loss to the environment (W)	717.851
12.	T_{r1}	Temperature of top rock segment (C)	19.5767
13.	T_{r2}	Temperature of second rock segment (C)	17.6453
14.	T_{r3}	Temperature of third rock segment (C)	15.8027
15.	T_{r4}	Temperature of fourth rock segment (C)	14.8890
.			
.			
.			
11+N	T_{rN}	Temperature of bottom rock segment (C)	14.1490

No.	Symbol	Item	Test Values[1]
DERIVATIVES (INITIAL VALUES OF DEPENDENT VARIABLES):[3]			
1.	T_{r1}	Temperature of top rock segment (C)	20
2.	T_{r2}	Temperature of second rock segment (C)	18
3.	T_{r3}	Temperature of third rock segment (C)	16
4.	T_{r4}	Temperature of fourth rock segment (C)	15
.	.		
.	.		
.	.		
N	T_{rN}	Temperature of bottom rock segment (C)	14

1/ From Willits et al. (1979, 1981).

2/ From Kimball and Jackson (1979), assuming the rock bed would have a thermal conductivity similar to dry sand.

3/ These test values are the initial temperatures for this example, which correspond to a time of -0.25 hour (the size of the time step for this example). The final temperatures for this time step were 19.5767, 17.6453, 15.8027, 14.8890, and 14.1490C. The temperatures for the next-to-last derivative iteration were 19.5693, 17.6079, 15.8046, 14.8016, and 14.2499 C.

Type 20 Arithmetic Calculator (ARITH)

PARAMETERS - up to 99
INPUTS - up to 40
OUTPUTS - 2
DERIVATIVES - 0

No.	Item	Test Values[1/]
PARAMETERS:		
1.	Number of parameters	6
2.	Number of inputs	1
3.	1st operation code. (If this parameter is not equal to 0 or -1, ARITH will put 2 inputs in the stack and perform the indicated operation.)	0
4.	2nd operation code	-1
5.		0.4
6.		1
etc.	etc.	

The operation codes are:

-1 - put next parameter on stack for use as a constant

0 - put next input on stack (enter)

1 - multiply

2 - divide

3 - add

4 - subtract

5 - exponentiate

6 - $\log_{10}$

7 - negate

8 - change negative number to zero

9 - logical "OR" (choose largest)

10 - logical "AND" (choose smallest)

Type 20 Arithmetic Calculator (Cont'd)

No.	Symbol	Item	Test Values 1/
INPUTS:			
1.	X_1		1.0
2.	X_2		-
etc.	etc.		-
OUTPUTS:			
1.	Y	The result of the arithmetic operations on the inputs.	0.4
2.	1-Y	This gives an output of opposite value for control logic.	0.6

1/ This set of parameters multiplies the Input 1 (1.0) by 0.4 to give Output 1 equal to 0.4.

Type 21 On-Off Thermostat (OSTAT)

PARAMETERS - 2
INPUTS - 2
OUTPUTS - 2
DERIVATIVES - 0

No.	Symbol	Item	Test Values[1/]
PARAMETERS:			
1.	T_s	Set-point temperature (C)	20
2.	Mode	1 for absolute, 2 for differential	1
INPUTS:			
1.	T_1	Temperature (C) (or other variable)	25
2.	T_2	Temperature (C). If Mode = 2, differential is computed as $T_1 - T_2$.	25
OUTPUTS:			
1.	γ_1	0 if $T_1 > T_s$; 1 if $T_1 < T_s$ Use this output for turning on heaters. If mode = 2, $T_1 - T_2$ is used in the above criteria in place of T_1.	0
2.	γ_2	$1 - \gamma_1$ Use this output for turning on coolers.	1

Type 22 Multistage Thermostat (MSTAT)

PARAMETERS - no. of set points + 2
INPUTS - 1
OUTPUTS - no. of set points * 2
DERIVATIVES - 0

No.	Symbol	Item	Test Values[1/]
PARAMETERS:			
1.	N_p	Total number of parameters = N + 2 where N is the number of set points.	7
2.	T_m	A master set point that divides heating from cooling. It should be in the dead band between heating and cooling. If have only heating (or only cooling), T_m can be given a value above (or below) all the other set points.	20
3.	T_{s_1}	Lowest set point for lowest (coldest) stage of heating	13
4.	T_{s_2}	Second lowest set point	15.5
5.	T_{s_3}	Third lowest set point	24
.			
.			
.			
N+1	$T_{s(N-1)}$	Second highest set point	26.5
N+2	T_{s_N}	Highest set point	29.5
INPUTS:			
1.	T	Input temperature (or other variable)	15.2124
OUTPUTS:			
1.	γ_{h1}	Heater control variable for lowest stage (= 1 when $T < T_{s_1}$)	0
2.	γ_{c1}	$1 - \gamma_{h1}$ opposite logic for lowest stage cooler control variable)	1
3.	γ_{h2}	Heater control variable for second lowest stage	0.335500
4.	γ_{c2}	$1 - \gamma_{h2}$	0.664500
5.	γ_{h3}	Heater control variable for third lowest stage	1
6.	γ_{c3}	$1 - \gamma_{h3}$	0

Type 22 Multistage Thermostat (Cont'd)

No.	Symbol	Item	Test Values[1]
2N-3	$\gamma_{h(N-1)}$	Heater control variable for second highest stage	1
2N-2	$\gamma_{c(N-1)}$	$1 - \gamma_{h(N-1)}$	0
2N-1	γ_{hN}	Heater control variable for highest stage	1
2N	γ_{cN}	$1 - \gamma_{hN}$	0

---

[1] These parameters define a thermostat with heating stages of 13 and 15.5 C and cooling stages of 24, 26.5, and 29.5 C. The input for the previous iteration was 15.2708. The second stage heater outputs for the previous and second previous iterations were 0.334141 and 0.33387, respectively. See Time 0 for the Solar Greenhouse System Example.

Type 23 Curtain Heat Exchanger (CXR)

PARAMETERS - 2
INPUTS - 5
OUTPUTS - 6
DERIVATIVES - 0

No.	Symbol	Item	Test Values
PARAMETERS:			
1.	A	Heat exchange area (m^2)	1/ 120
2.	U	Overall heat transfer coefficient ($W/m^2 \cdot C$)	2/ 7
INPUTS:			
1.	T_{ai}	Temperature of air in space where curtain exchanger is hung (C)	41.4789
2.	m_a	Air mass flow rate (unused - for continuity only)	1.0
3.	W_{ai}	Humidity ratio of air in space where curtain heat exchanger is hung	0.0
4.	T_{wi}	Inlet water temperature (C)	25.5107
5.	m_{wi}	Water flow rate (kg/s)	3.7
OUTPUTS:			
1.	T_{ao}	Temperature of air in imaginary outlet air stream	28.6754
2.	m_a	Imaginary outlet air flow rate (kg/s) ($m_a = 1$ if $m_{wi} > 0$; otherwise $m_a = 0$)	1.0
3.	W_{ao}	Humidity ratio of imaginary outlet air stream ($W_{ao} = W_{ai}$)	0.0
4.	T_{wo}	Outlet water temperature (C)	26.3530
5.	m_{wo}	Water flow rate (kg/s) ($m_{wo} = m_{wi}$)	3.7
6.	Q	Rate of heat transfer from air to water (W)	13059.5

1/ Represents 5 curtains, each 6 m long by 2 m high.

2/ As measured in USWCL test greenhouse at 12:50 on 12 Sep 79 with no forced air movement.

Type 24 Passive Storage (PSTOR)

PARAMETERS - 4
INPUTS - 3
OUTPUTS - 5
DERIVATIVES - 1

No.	Symbol	Item	Test Values
PARAMETERS:			
1.	A	Total heat exchange area (m^2)	1/ 59
2.	U	Overall heat transfer coefficient ($W/m^2 \cdot C$)	2/ 4
3.	M_s	Total mass of storage material (kg)	1/ 2200
4.	c_s	Specific heat of storage material ($J/kg \cdot C$)	1/ 4190
INPUTS:			
1.	T_{ai}	Temperature of air in space where storage is located (C)	11.2292
2.	m_a	Air mass flow rate (unused - for continuity only)	1.0
3.	W_{ai}	Humidity ratio of air in space where storage is located	0.00652753
OUTPUTS:			
1.	T_{ao}	Temperature of air in imaginary outlet air stream	12.6664
2.	m_a	Imaginary outlet air flow rate (= 1 kg/s)	1.0
3.	W_{ao}	Humidity ratio of imaginary outlet air stream ($W_{ao} = W_{ai}$)	0.0065275
4.	T_s	Storage temperature (C)	17.4409
5.	Q	Rate of heat transfer from air to storage (W)	-1465.97
DERIVATIVES (INITIAL VALUE OF DEPENDENT VARIABLE): 3/			
1.	T_s	Temperature of storage material (C)	18.0

1/ Stack of 3.785 liter (1 gallon) plastic bottles as described in USWCL 1980 Annual Report for Greenhouse 1. There were 576 bottles to give 81 liters

of water per m^2 of greenhouse floor area. The overall dimensions of the stack were 1.3 m wide by 1.9 m long by 2.0 m high, so 45% of the stack was water. Eight percent of the stack was wood, leaving 47% air.

2/ From ASHRAE (1972, p. 357) for horizontal heat flow from still air to vertical surface reduced by 1/2 because interior bottle surfaces view each other and because air flow to the interior is restricted by long passages.

3/ This test value of 18.0 C is the initial temperature for this example, which corresponds to a time of -1.0 hour (the size of the time step for this example). The final temperature for this time step was 17.4409C. The temperature for the next-to-last derivative iteration was 17.3987 C.